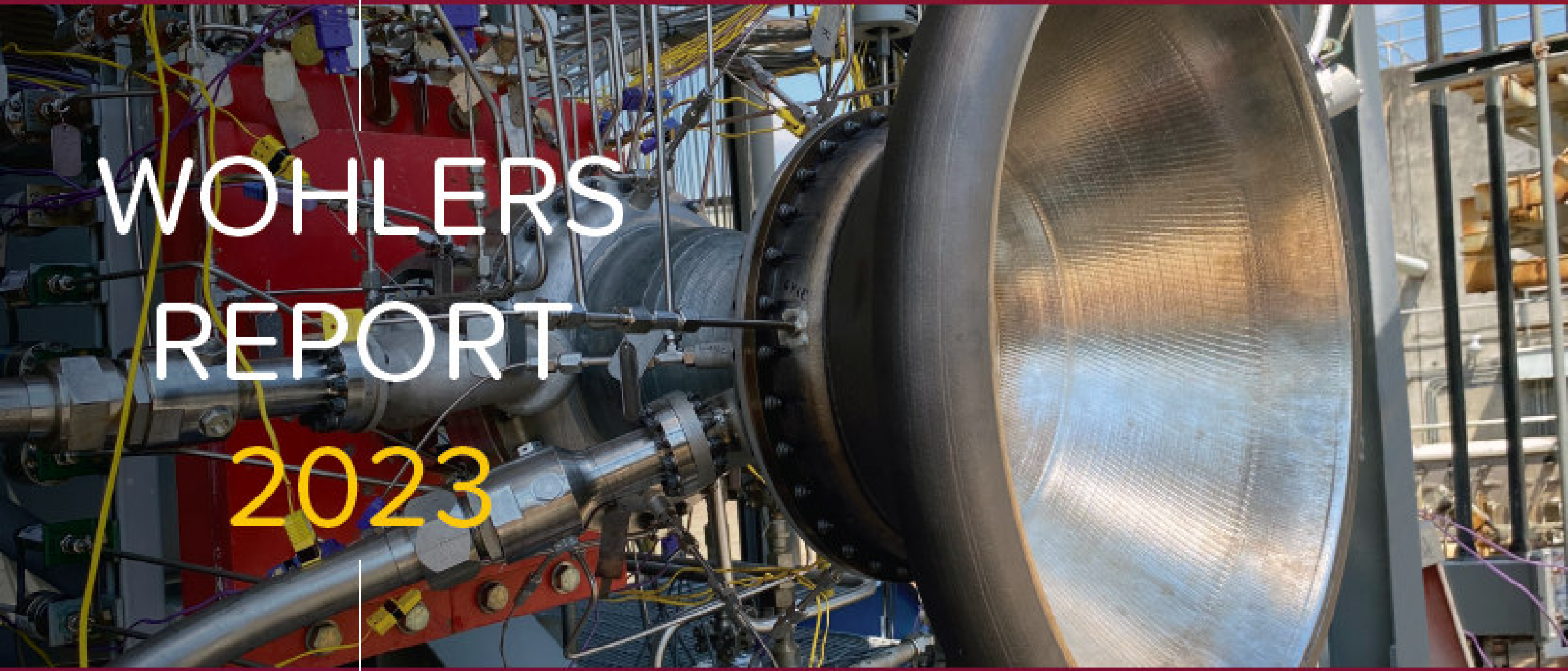

WOHLERS REPORT 2023

3D PRINTING AND ADDITIVE MANUFACTURING

GLOBAL STATE OF THE INDUSTRY

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Wohlers Report 2023

3D Printing and Additive Manufacturing
Global State of the Industry

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1 2 3 4 5 6 7 8 9 10 24 23 22

TABLE OF CONTENTS

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Wohlers Associates is grateful for the generous input from 119 service providers, 128 manufacturers of additive manufacturing systems, and 27 producers of third-party materials.

The following 92 contributors authored sections of this report. Wohlers Associates sincerely appreciates their expertise, hard work, and kind support.

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Remarks from ASTM International

ASTM International has been making strides to expand its offerings beyond developing industry-relevant and globally recognized standards to support the industrialization of additive manufacturing (AM) across sectors. The Additive Manufacturing Center of Excellence (AM CoE) is an ASTM International initiative that accelerates standards development. The AM CoE offers dedicated research, education and workforce development programs, and the Consortium for Materials Data and Standardization. The consortium supports companies of all sizes in the AM ecosystem to collaborate on standardizing the requirements and best practices for materials data generation and use.

With the acquisition of Wohlers Associates in 2021, the AM CoE has expanded its offerings to provide specialty reports, advisory and consultancy services, and industry guidance documents. The AM CoE has also started a major modernization strategy to enhance the offerings of Wohlers Associates, including a new website with a fully automated ordering process and fulfilment system. Also, strategies have been implemented to streamline customer service and improve the *Wohlers Report* by refining the design and the way information and data are captured and analyzed.

Two specialty reports were published in late 2022 and early 2023. The second edition of the report on the post-processing of AM and 3D-printed parts offers a broad range of methods and techniques for finishing parts. The additive construction report provides a comprehensive review and analysis of specific applications and materials.

The AM value chain continues to experience rapid advancements as new technology variants enter the market. *Wohlers Report 2023* captures every relevant move in the industry and provides accurate and up-to-date information. The report offers insightful analysis of the latest trends, growth drivers, and challenges shaping the global AM market. It continues as an invaluable resource for industry professionals, policymakers, and researchers seeking to understand the current state of the market and where AM is headed.

We welcome feedback on the report and are committed to continuously improving it and other offerings to support the industrialization of AM.

Mohsen Seifi, PhD
Vice President
Global Advanced Manufacturing Programs
ASTM International, Washington, DC U.S.

A note from Terry Wohlers

I am excited about the publication of *Wohlers Report 2023*. This annual report has served as the undisputed industry-leading publication on AM and 3D printing worldwide for nearly three decades. This edition marks its 28th consecutive year of publication.

The AM industry grew 18.3% in 2022 to $18.027 billion worldwide, according to extensive research for this report. How does this compare to the first edition of the *Wohlers Report* published in 1996? The industry generated an estimated $295.1 million the previous year, which means the industry has grown by 61 times over this period.

Today, we are seeing single investments and company acquisitions many times larger than the AM industry was 28 years ago. Back then, eight companies were developing and selling AM systems. This number has increased to more than 250 by the end of 2022.

What has not changed since the first edition? Organizations of all types and sizes around the world continue to benefit from AM for concept modeling and prototyping. Countless companies are also using the technology for rigorous functional testing of new designs. Some companies are now using AM for end-use part production, yet it remains the next frontier across most industrial sectors.

Applications of AM have also developed impressively. Tens of thousands of aerospace parts produced with AM have flown in planes, rockets, and satellites. Tens of thousands of patients have received dental products and orthopedic implants made by AM. In 28 years from now, people will receive patient-specific body parts printed and grown from living cells taken from their bodies. 3D-printed food, medicine, electronics, and fashion products will become common.

I hope *Wohlers Report 2023* helps you and your organization make the best decisions related to AM, especially those of strategic value. A team of 12 professionals from Wohlers Associates and ASTM International and 92 expert contributors from 35 countries were central to the development of this report. Detailed input was provided by hundreds of service providers, producers of machines and materials, and a wide range of users of AM. We are grateful for the access and trust they have granted us over the years.

If you like the report, let us know. If you have suggestions for a future edition, we would like to hear from you. I sincerely thank you for your support.

Terry Wohlers, MSc, Dr. h.c., FSME
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Wohlers Associates, powered by ASTM International
Fort Collins, Colorado U.S.

About the Authors and Editors

At the core of *Wohlers Report 2023* is a global team of five principal authors spanning four continents. These individuals collected, analyzed, and organized contributions and data from around the world. They also researched and authored many sections of the report. A vital part of the group is its editorial, analytics, and project management team. These professionals played a key role in the development of the report.

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Abbreviations, Acronyms, and Conversions

Within this report and the broader AM industry, many abbreviations, acronyms, and conversions are used. The following are some of the most common. See Appendix A for a glossary of terms and definitions.

ABS	acrylonitrile butadiene styrene	PA	polyamide (known as nylon)
AM	additive manufacturing	PBF	powder bed fusion
BJT	binder jetting	PBT	polybutylene terephthalate
CAD	computer-aided design	PEEK	polyether ether ketone
CNC	computer numeric control	PEI	polyethylenimine
CT	computed tomography	PEKK	polyetherketoneketone
DED	directed energy deposition	PETG	polyethylene terephthalate glycol
DfAM	design for additive manufacturing	PLA	polylactic acid
DLP	digital light processing	PU	polyurethane
DOD	U.S. Department of Defense	SHL	sheet lamination
EBM	electron beam melting	SMEs	small- and medium-sized enterprises
EDM	electrical discharge machining	TPU	thermoplastic polyurethane
FDA	U.S. Food and Drug Administration	ULTEM	polyetherimide product from Sabic
MEX	material extrusion	UV	ultraviolet
MJF	multi jet fusion from HP	VPP	vat photopolymerization
MJT	material jetting	WAAM	wire-arc additive manufacturing

Many currencies are used throughout the report. The following exchange rates are from early March 2023.

Currency	US$1 =	Currency	US$1 =
Australian dollar	1.48	Norwegian krone	10.48
British pound	0.83 (£1=US$1.20)	Polish zloty	4.32
Canadian dollar	1.36	Singapore dollar	1.34
Chinese yuan	6.87	South African rand	17.81
Euro	0.94 (€1=US$1.07)	South Korean won	1,306
Danish krone	6.87	Swedish krona	10.44
Japanese yen	136.20	Swiss francs	0.94
New Zealand dollar	1.60	Turkish lira	18.88

Throughout the report, both metric and imperial units are provided. The following table provides some common conversions.

Metric	Imperial
1 m	39.37 in
1 mm	0.039 in
1 µm	39.37 µin
1 m²	10.76 ft²
1 kg	2.205 lbs

PART 1: INTRODUCTION

Focus of this report

The *Wohlers Report*, published annually, is a comprehensive compilation and analysis of additive manufacturing (AM) and 3D printing worldwide. These terms are used interchangeably throughout the industry and this publication. For 28 years, this report has provided a thorough review of the global AM industry.

Wohlers Report 2023 was written for any individual or organization seeking clear insight into the AM market. Groups that purchase this report include product development and manufacturing companies, service providers, startups, researchers, educators, and analysts. Others include investors, government agencies, and developers of industry standards and regulations.

An important part of this report is its comprehensive coverage of the AM industry's growth. Part 3 of the report includes revenues and other growth information, complete with tables and charts illustrating relevant trends and industrial segments. The foundation of this reporting is our nearly three decades of data and information from the industry. Organizations providing this data include producers of AM systems, software, and materials, as well as service providers and customers. The information in this report has been produced with the help of surveys, interviews, research, and an international network of contributors and contacts.

The report serves as a "barometer" of the industry's health and future. No other publication in the AM industry includes 28 years of hard data as its basis for calculating growth, analyzing trends, and forecasting the future.

Current technologies and trends related to final part production are discussed in detail. Also covered are mergers and acquisitions, the patent landscape, and legal issues in the industry.

The report provides updates on recent technical developments, advances in AM materials, and 3D scanning. *Wohlers Report 2023* documents government-sponsored research and development, collaborations, consortiums, and the activities of many academic and research institutes around the world.

The report concludes with a discussion of the emerging applications and trends in AM's developing ecosystem. It provides insight into the future—what is driving the industry today and what to expect in the years ahead—to assist in strategic planning and investing.

The 2023 edition features expanded discussion on investments and startups in the AM industry. The report includes 55 charts and graphs, 101 tables, and 268 images and illustrations.

Wohlers Report 2023 can be used as a tool for education and knowledge acceleration. Information can provide a competitive edge, and that is what this report aims to do. Readers new to AM will gain a comprehensive understanding of the technology and industry. AM veterans will benefit from the up-to-date information on growth, trends, and the latest and most important developments.

Supplemental online information, as shown in the following table, is included with *Wohlers Report 2023*. This information is accessed by live links within this report. These documents are available exclusively to those who purchase this report. Enter "wohlers" as the password for each of them.

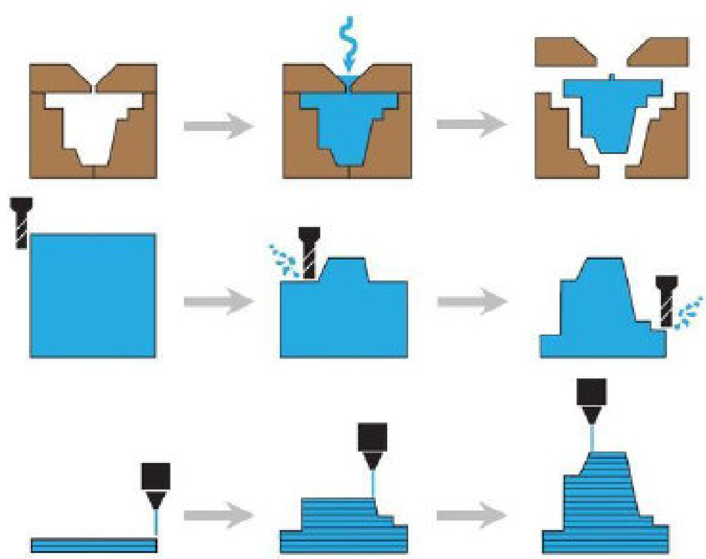
Document name	Description
www.wohlersassociates.com/castmetal2023.pdf	Cast metal parts (7 pages)
www.wohlersassociates.com/history2023.pdf	History of AM (61 pages)
www.wohlersassociates.com/metalam2023.pdf	Metal AM processes (14 pages)
www.wohlersassociates.com/scan2023.pdf	3D scanning systems (4 pages)
www.wohlersassociates.com/3Dscanning2023.pdf	3D scanning (5 pages)

Introduction to AM and 3D printing

AM, as defined by the ISO/ASTM 52900 terminology standard, is the process of joining materials to make parts from 3D model data. Usually, material is joined layer upon layer, as opposed to subtractive and formative methods of manufacturing. Historical terms for AM include additive fabrication, additive processes, additive techniques, additive layer manufacturing, and layer manufacturing. Other terms include 3D printing, direct digital manufacturing, solid freeform fabrication, rapid manufacturing, and rapid prototyping.

The following schematic diagrams illustrate differences in the three main methods of manufacturing. Formative manufacturing processes, depicted in the top row, use tooling, such as a mold or die set, to form a part. Examples are injection molding, die casting, and investment casting. Other formative processes use tooling to deform feedstock. They include thermoforming, forging, rolling, extrusion, and stamping.

Fig. 1. Diagrams of formative (top), subtractive (middle), and additive manufacturing (bottom)



Subtractive manufacturing processes, shown in the middle row, create or reshape a part by removing material. Material is milled, turned, cut, or ground. AM processes, represented in the bottom row, involve layer-by-layer addition of material to create a part.

The term "3D printing" is often used synonymously with additive manufacturing. 3D printing has become the de facto standard term for commercial use. The academic and research communities often prefer the term "additive manufacturing." The terms additive manufacturing and 3D printing have the same meaning and are used interchangeably in industry and throughout this report.

Processes and feedstock

AM encompasses seven distinctly different process categorizations as defined in the ISO/ASTM 52900 terminology standard. Each of these seven categories is differentiated by the form of feedstock and/or the binding process used to join the material. These processes and abbreviations—also defined by this standard—are provided in the following table.

AM process	Abbreviation
Binder jetting	BJT
Directed energy deposition	DED
Material extrusion	MEX
Material jetting	MJT
Powder bed fusion	PBF
Sheet lamination	SHL
Vat photopolymerization	VPP

Feedstock is available as filament, liquid, powder, pellets, paste, sheet material, and wire. Parts can be created in a layer-by-layer fashion by extruding, jetting, photocuring, laminating, spraying, or thermally fusing materials. These materials and processes are described in more detail in Part 2 of this report.

The following table shows the intersections between the AM processes and the available material families and applications, such as investment and sand casting. Some processes are inherently linked to specific materials.

	BJT	DED	MEX	MJT	PBF	SHL	VPP
Thermoplastic polymers	x		x		x		
Thermoset polymers				x			x
Elastomer polymers			x	x	x		x
Composites[1]	x		x	x	x	x	x
Metals	x	x	x	x	x	x	x
Graded/hybrid metals[2]		x			x	x	
Ceramics	x		x	x	x		x

	BJT	DED	MEX	MJT	PBF	SHL	VPP
Investment-casting patterns	x		x	x	x		x
Sand molds and cores	x		x		x		
Paper/wood[3]	x		x			x	

Source: Wohlers Associates

Footnotes:
1 Includes filled materials.
2 Hybrid materials are typically produced using ultrasonic SHL. Graded materials are produced with DED systems.
3 Includes a binding agent.

Putting AM to work

The application of AM may be driven by enhancing part performance. This can include creating desirable geometric shapes that are either impossible or very expensive to produce using formative or subtractive manufacturing. Examples are tools with conformal cooling channels, topology-optimized parts, and parts with internal cellular or lattice structures. Creating unique microstructures can enhance product performance. This includes aligned grain structure, refined grains, functionally graded composition and microstructure, and preferred crystallographic texture.

AM applications may be driven by cost reduction compared to other manufacturing methods, particularly formative manufacturing, which requires part-shape-specific tooling. Tooling is expensive and the cost increases with design complexity.

Formative processes are cost-effective for large production runs of identical parts. The cost of tooling is spread over many parts. For example, if 100 identical parts are needed and the tooling cost is $30,000, each part would need to have a minimum value of $300 to recover the tooling cost alone. If the production run is one million identical parts, the tooling cost could be recovered by adding only $0.03 to each part. For this reason, AM is best considered for short production runs and custom part designs. A detailed cost analysis is necessary for any given design and production quantity to determine if AM is cost-effective.

Another cost impact is a part's size. Typically, AM favors production of small parts rather than large ones. As described in Part 4, most AM processes are penalized with large-volume parts. This is largely due to exponentially increased build time, which lowers the production rate. The result is increased part cost associated with AM-machine depreciation and a drop in productivity and profitability.

As indicated in Part 2 of this report, the cost of AM feedstock is often an order of magnitude higher than associated conventional manufacturing feedstock. Therefore, AM becomes less attractive for large volumes due to high material costs. A few AM processes are designed to accommodate low-cost feedstock and large-volume parts. For metals, directed energy deposition

(DED) can produce parts of more than 1 m (3.3 ft) in length. Large parts, such as composite tooling, car bodies, and sections of buildings, are made using material extrusion (MEX) processes with polymer or concrete feedstock.

AM is used to build models, prototypes, patterns, tooling, and production parts in plastics, metals, ceramics, glass, composites, and biomaterials. AM systems produce parts using 3D models created by CAD software, 3D scanning systems, medical imaging equipment, and even video games.

Design and manufacturing organizations use AM parts for products in the consumer, industrial, medical, and military sectors, to name a few. Parts for automobiles, aircraft, consumer electronics, energy systems, and medical devices are just a few of a long list of products that benefit from AM.

As a tool for rapid product development, AM can reduce time to market, improve product quality, and reduce costs. Quick product iterations streamline and expedite the product development process. As a visualization tool, AM helps companies reduce the likelihood of delivering a flawed product to the marketplace. Physical models allow companies to gain early feedback from management, experts, customers, and stakeholders.

The use of AM for tooling is becoming a mature application. Historically, an application of AM was rapid tooling and injection-mold tooling inserts with the inclusion of conformal cooling channels. Other efforts have focused on using AM to produce manufacturing and assembly tools, such as jigs, fixtures, gauges, templates, and drilling and cutting guides.

AM significantly impacts the way some companies design and manufacture products. Large and small organizations successfully apply the technology for the production of finished goods. Wohlers Associates believes this practice will grow to become the largest and most significant application of AM.

A growing number of industrial sectors and geographic regions are adopting AM. Its impact is expected to become even more significant in the future. The industry continues to expand with the introduction of new types of AM machines, materials, applications, workflows, software products, and business models.

History of AM

Who would have thought the foundations of AM were developed and even demonstrated more than a century ago? 3D printing processes first made their appearance over three decades ago, with machines being beta tested in 1987 before full commercialization one year later. Although many companies achieved success as they developed new processes and bold business strategies, not all ventures were successful. Nevertheless, this history continues to be written through innovative ideas and pioneering entrepreneurs.

1960s to the modern era

Delve into the historical developments of AM from its earliest inventions in the 1960s to March 2022 with an exclusive, 61-page document available for download at wohlersassociates.com/history2023.pdf. Use "wohlers" as your password to unlock this content.

March 2022 to March 2023

In March 2022, Diamond Age raised $50 million in Series A funding led by Prime Movers Lab. The company claims its printers will speed the process of building homes. The company hopes it will help address an estimated shortage of seven million homes in the U.S.

Also in March, Japanese document printer and electronics manufacturer Epson announced its first 3D printer, an MEX system. Epson says it will work with a range of polymers and metals in pellet form.

In April 2022, Divergent closed its Series C funding after raising $160 million. The money is being used to complete the company's integrated manufacturing platform, with AM being at its center.

In May, GE Renewable Energy announced it had taken a minority share in COBOD, a Danish manufacturer of a system that deposits concrete, layer by layer, for construction applications.

Fig. 2. Additive construction project, courtesy of COBOD

U.S. President Joe Biden announced the launch of AM Forward, a program to encourage the use of AM among American manufacturers. It is designed to promote collaboration and provide incentives for companies to adopt the technology. Initial participating companies include GE Aviation, Honeywell, Lockheed Martin, Raytheon, and Siemens Energy. They are encouraging and helping small companies to build capacity in AM.

Also in May 2022, metal powder producer 6K raised $102 million in Series D funding in a round led by Koch Strategic Platforms. Part of the money will be used to expand the production of powders for metal AM. MakerBot and Ultimaker, two producers of desktop MEX systems, agreed to combine their operations into a single entity. Stratasys is investing $62 million of new funding in the combined company, renamed as Ultimaker.

Contract manufacturer Jabil, with its 100 facilities in 30 countries and 260,000 employees, launched a polymer for PBF systems. The material was developed at Jabil's innovation center in Minnesota. The company claims it provides improved material properties over alternative polyamide powders.

Fig. 3. Parts printed with Jabil PK 5000 material, courtesy of Jabil

In June 2022, Daimler bus owners gained access to Omniplus, a digital inventory of 100 spare parts available for printing. Germany's HZG Group raised €60 million to establish the HZG Additive Manufacturing Tech Fund. It supports early-stage AM startups in Germany, Austria, and Switzerland. The fund was established by Kerstin Herzog and Frank Carsten Herzog, founders of Concept Laser, which was acquired by GE in 2016.

In July 2022, VulcanForms emerged from stealth mode to announce the development of a large metal PBF system. The printer uses multiple lasers with two megawatts of power. VulcanForms was spun out of MIT and is valued at more than $1 billion, according to the company. European regulators approved the MyBone 3D printing material from Cerhum for use in patients to produce patient-specific hydroxyapatite implants for maxillofacial and orthopedic applications.

Fig. 4. MyBone implant, courtesy of Cerhum

Markforged acquired Swedish binder jetting (BJT) company Digital Metal, a subsidiary of powder producer Höganäs AB. The price was $33.5 million and about 4.1 million shares of Markforged stock, which trades on the New York Stock Exchange. The transaction expands Markforged offerings into BJT, complementing its existing metal and composite MEX systems.

Also in July, the corporate venture arm of CEMEX, a Mexican producer of cement, ready-mix concrete, and aggregates, invested in COBOD. CEMEX joined GE Renewable Energy and construction materials company Holcim Group as investors in the venture. Boston Micro Fabrication (BMF) raised $43 million in Series C funding to scale its operations. BMF, with roots in China, specializes in developing 3D printers for small, precision parts. The funding round was led by Shenzhen Capital Group.

In August 2022, Stratasys acquired Covestro's AM materials business for about €43 million. The agreement includes a potential earnout tied to performance of up to €37 million. The deal, which was expected to close in Q1 2023, includes R&D operations and intellectual property of Covestro's AM materials unit.

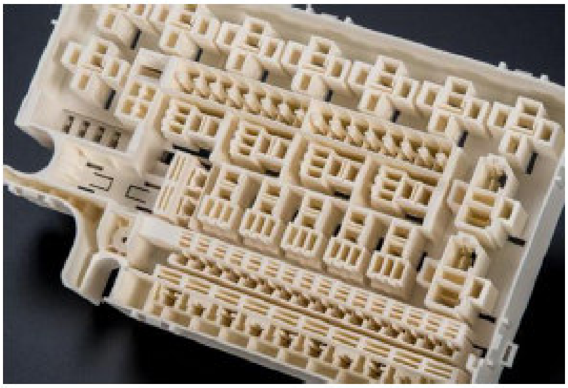


Fig. 5. Fuse box printed using Covestro material, courtesy of Covestro

Bioprinting company Prellis Biologics raised $35 million in Series C funding in a round led by Celesta Capital. As of August 2022, Prellis had raised a total of $64.5 million in funding since its founding in 2016. Carbon, manufacturer of vat photopolymerization (VPP) systems, acquired Paramatters, an AM software developer. The acquisition will add advanced tools, such as topology optimization, to Carbon's software products used to design parts for printing on the company's systems. Terms of the acquisition were not disclosed. Paramatters was previously a part of the Xponential Works business incubator.

In September, Nikon agreed to acquire all outstanding shares of metal powder bed fusion (PBF) system manufacturer SLM Solutions. Nikon will pay €20 per share, a premium of 75% over the September 1, 2022, closing share price on the Xetra Exchange. The acquisition took place in January 2023.

Also in September, HP launched the Metal Jet S100, a BJT metal 3D printer. HP announced the start of commercial sales of machines at the International Manufacturing Technology Show, perhaps better known as IMTS, in Chicago, Illinois.

Transportation and logistics company DB Schenker announced it will supply spare parts from a virtual warehouse by 3D printing them close to where they are needed. DB Schenker is a division of Deutsche Bahn, Germany's national rail company.

In October 2022, Los Angeles company SprintRay raised $100 million in Series D financing led by Softbank. SprintRay develops and sells a range of in-office VPP dental printers.

In December 2022, California company Continuum raised $36 million. The company will use the funding to accelerate development of AM metal powders made from recycled materials. Continuum is a spinoff from Molyworks Materials Corp.

In January 2023, five energy companies agreed to collaborate on standardizing the supply of spare parts produced by AM from a digital inventory. Companies joining the collaboration are ConocoPhillips, Equinor, Shell, TotalEnergies, and Vår Energi.

In February 2023, Desktop Metal laid off about 15% of its global workforce as part of a cost-cutting program. It was expected to save the company $50 million. Stratasys received Class II FDA clearance for making dentures using its full-color J5 DentaJet material jetting (MJT) system. Fabric8Labs raised $50 million in a Series B investment round led by New Enterprise Associates. The money is being used to develop the company's proprietary electrochemical metal AM process.

The U.S. Department of Energy announced $30 million in funding to advance the development of composite materials and AM for large wind turbine projects. The money is covering the production of blades and other turbine parts.

In March 2023, EOS partnered with Bauer to produce custom liners for hockey helmets. A player's head is scanned, and a custom liner is manufactured on a polymer PBF system. The personalized design is lighter and more comfortable, according to the two companies. Also in March, machine manufacturer 3D Systems was ordered to pay up to $27 million in fines to the U.S. Departments of Commerce, Justice, and State for violating export restrictions. The fines were levied for the illegal transfer of data without a license to the company's subsidiary in China in connection with parts for defense projects.

Sakuú, a manufacturer of 3D-printed batteries, announced it would merge with Plum Acquisition Corp., a special-purpose acquisition company, and would be traded on the Nasdaq stock exchange. The transaction implies an enterprise value of more than $700 million. In connection with the transaction, the company planned to raise an additional $100 million in funding. Florida AM service provider Sintavia was contracted to establish a dedicated AM facility for the U.S. Navy. The center will support the United States Naval Nuclear Propulsion Program under development for the Navy's submarine programs.

Later in March, Zeda closed $52 million in financing. The manufacturing services company is using the Series B funding to build out its facility in Cincinnati, Ohio. The company also plans to construct additional manufacturing facilities worldwide. Nano Dimension formally announced a cash offer to acquire all shares in Stratasys that it does not already own. The offer was to acquire at a premium of 36% above the share price. At the time of the offer, which Stratasys declined, Nano Dimension owned about 14.5% of Stratasys stock, acquired in open market trading since July 2022.

Industry survey

Wohlers Associates receives data and insight from industry insiders, producers of machines and materials, service providers, and others. The information results in unparalleled breadth and depth of information for inclusion in this report. It supports the tracking of the AM industry, estimating its size and forecasting the future. No other resource in the AM industry provides this level of information and detail. The results and takeaways from this report are based on 28 years of collecting and analysing data and sharing market intelligence.

For this edition of the report, 119 service providers worldwide responded to a detailed questionnaire. Also, 128 manufacturers of AM systems (both industrial and desktop systems) and 27 producers of third-party materials responded by providing information and data. This extensive body of data enriches many sections of this report. These companies provided information based on knowledge of their customers and the AM industry. In total, 274 companies responded to our request for information and data.

Of the 119 service providers responding, 39 are from the U.S., 10 from Germany, 10 from the UK, and six each from India and Switzerland. Five are from Italy, four from Sweden, and three each from Canada, Finland, South Africa, and Turkey. Two each are from Australia, Belgium, Czech Republic, Denmark, the Netherlands, New Zealand, and the UAE. One each is from Argentina, Cyprus, Greece, Hungary, Israel, Japan, Malaysia, the Philippines, Portugal, Saudi Arabia, Singapore, Spain, and Thailand. The following chart shows a breakdown of the contributing service providers by country.

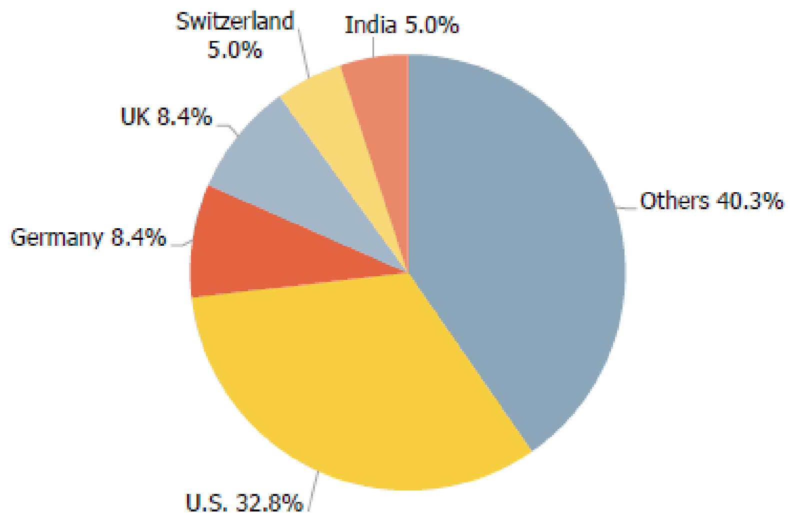
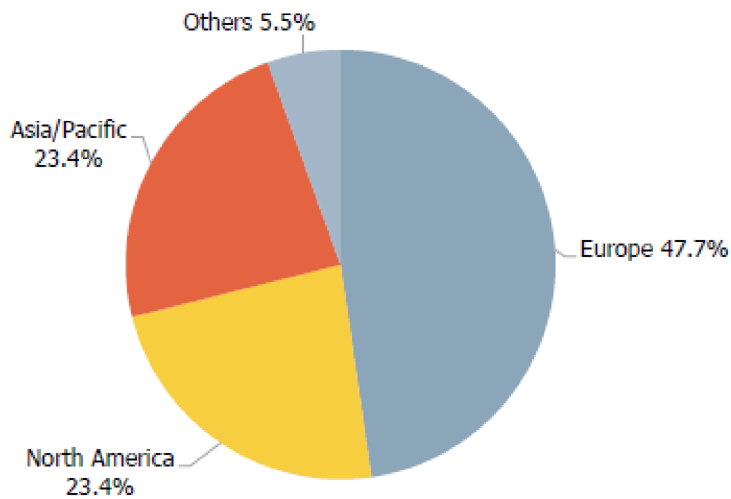


Fig. 6. Contributing service providers by country; source: Wohlers Associates

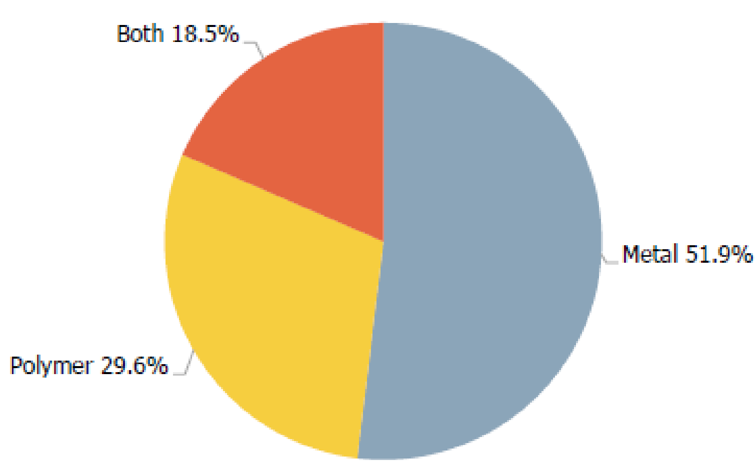
Of the 128 system manufacturers that provided data, 27 are from the U.S., 14 from Germany, and nine from China. Eight are from Italy, seven from Japan, and six from Austria. Five each are from South Korea and the Netherlands, and four each from Australia, France, Israel, and Turkey. Three each are from Canada, Poland, and Spain. Two each are from Belgium, Finland, India, Sweden, and Switzerland. One each is from Argentina, Colombia, Czech Republic, Luxembourg, New Zealand, Russia, Singapore, Slovenia, South Africa, Taiwan, the UK, and Ukraine. The following shows a breakdown of the contributing system manufacturers by geographic region.

Fig. 7. Contributing system manufacturers by region; source: Wohlers Associates



Of the 27 third-party producers of materials for AM, 14 produce metal feedstock, eight produce polymer feedstock, and five produce both.

Fig. 8. Contributing third-party material providers by material category; source: Wohlers Associates



Applications

New applications of AM are emerging as processes, materials, and software tools evolve. When 3D printing was initially commercialized, it was called rapid prototyping, reflective of the technology's main application. Over the past two decades, and especially in recent years, AM has been used increasingly for tooling and production applications.

For this edition of the report, service providers were asked, "How do your customers use the AM parts you provide?" (See the previous section titled "Industry survey" for the location of these companies.) System manufacturers were asked, "How do your customers use the parts built on your systems?" The survey included the following options:

– Prototyping
– Cosmetic/appearance and presentation models and visual aids
– Functional parts for engineering fit and function testing, assembly, etc.
– Tooling
– Polymer and sand patterns, cores, and molds
– Metal molds/dies created directly on metal AM systems
– Jigs, fixtures, drill/cutting guides, gauges, assembly aids, etc.
– Final part production
– End-use parts (sold to and used by a final customer)
– Education/research
– Other

The following chart shows how organizations are using industrial AM systems for a range of applications.

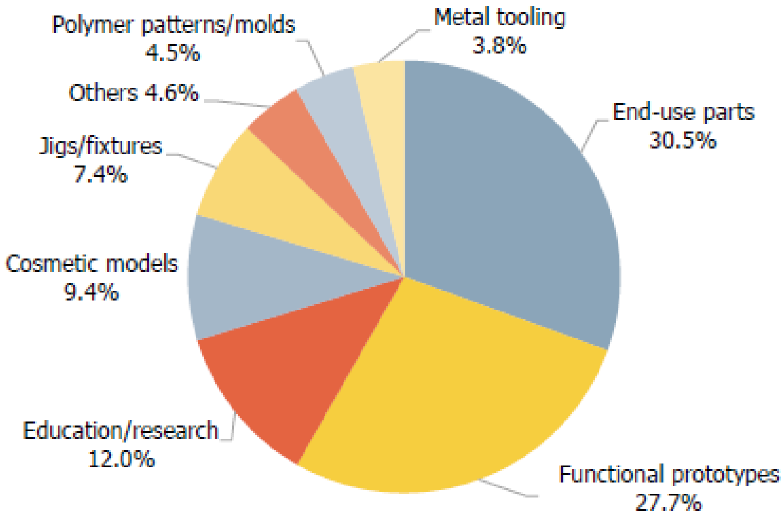


Fig. 9. Industrial uses for AM applications; source: Wohlers Associates

Prototyping

Concept modeling and prototyping were the first applications of AM. The following image is the first 3D-printed part sent to Wohlers Associates in 1987. It is a model of an automotive distributor cap, built by 3D Systems about a year before commercial (non-beta) machine sales began. Today's automobiles have electronic ignition and do not use a distributor to connect the spark plug wires to the rotor. What has not changed over the years is the use of AM to create prototypes quickly. The quality of 3D-printed models and prototypes has improved significantly over time.

Fig. 10. Prototype of an automotive distributor cap produced in 1987 using VPP, courtesy of 3D Systems

Service providers and system manufacturers reported that cosmetic models represent 9.4% of all applications. They are used to communicate design intent and clarify ambiguities from computer models and engineering drawings. They are also used for presentations at meetings and events.

A rapidly produced prototype can communicate concepts efficiently and effectively. This is particularly helpful for consumer products, architectural projects, and surgical planning. The following is an image of a Bluetooth speaker concept created by Priority Designs. Using AM, five variations were printed overnight for review by designers and customers.

Fig. 11. Full-color 3D-printed prototype speakers, courtesy of Priority Designs

Functional prototypes are generally created to test fit and function and represent 27.7% of applications. These models help remove ambiguity and abstraction by physically demonstrating an assembly and use. They often help validate designs and identify issues with tolerance, fit, alignment, and function before final parts are manufactured. Identifying these issues at an early stage can save thousands or even millions of dollars in redesign, tooling costs, and scrap.

The following image shows a drill design prototype created on a 3D printer from Formlabs. The prototype was strong enough to perform functional testing.

Fig. 12. Drill prototype used for functional testing, courtesy of Formlabs

Prototypes are critical in product development. The following image shows a prototype for the Vision electric race car. It features 15 3D-printed parts, including the nose wing and rear wings. They were produced on a large-format 3D printer from Builder.

Fig. 13. Prototype race car featuring 3D-printed parts, courtesy of Builder

Some companies are using AM for both prototyping and series production applications. 3D-printed parts initially support prototyping and testing and are later used for production. One benefit to this approach is using the same process and material for both prototyping and manufacturing. With most product development and manufacturing, this does not occur. While prototyping a design, a company can also test the manufacturing process and workflow, including methods of post-processing and part inspection.

The following is a suction nozzle designed by Süss & Friends to consolidate several mechanical and electrical parts. The nozzle was designed and prototyped, and a small quantity went into production using polymer PBF. In the prototyping stage, the post-processing technique was changed after discovering that residual powder was trapped within the device. By resolving this issue when prototyping, Süss & Friends delivered the product more quickly.

Fig. 14. Suction nozzle prototyped and manufactured using polymer PBF, courtesy of Baumer and Süss & Friends

Tooling

According to ISO/ASTM 52900, prototype tooling includes molds, dies, and other devices used for prototyping purposes. This type of tooling is also referred to as "bridge tooling" or "soft tooling." Included in this definition is tooling used to test designs and/or produce end-use parts while final production tooling is being manufactured. "Rapid tooling" is intended to produce tooling with reduced lead time compared to conventional manufacturing.

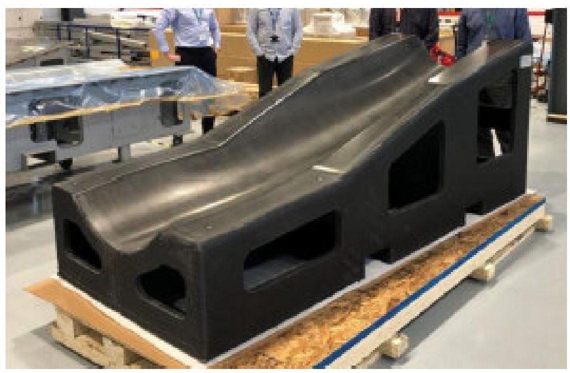


Fig. 15. Mold tooling made using MEX, courtesy of DAE Systems

The 3D printing of master patterns for mold creation has been applied for decades. Any AM technology can be used for this process, but VPP creates parts that require minimal post-processing. Silicone rubber is poured onto and around an AM master pattern to create a soft tool used to cast multiple urethane parts. The casting process may use a two-part thermoset polymer that mimics the properties of injection-molded thermoplastics.

Silicone rubber tooling and urethane casting, also referred to as vacuum casting, have been used for decades to produce prototype, pre-production, and even production parts in relatively low volumes. The production quantities can be 25–50 parts but can vary depending on the features of the part and durability of the mold material. The following image shows a molded part using AM for the master pattern.

Fig. 16. 3D-printed master pattern (left), silicone mold (center) and final part (right), courtesy of SioCast

It is possible to 3D print inserts for relatively simple, single-cavity plastic injection molds. The mold can be used to create parts using the final production material prior to investing in expensive, multi-cavity metal tooling. By 3D printing mold inserts directly, companies can iterate quickly and optimize a design before producing the final tooling.

The following image shows a four-part mold assembly in an injection-molding press. The mold inserts, in orange, were produced in a ceramic-filled polymer using a VPP system from Fortify. The molded parts were created for DeMarini Sports to prototype a new baseball bat cap. Twenty parts in different materials were produced for design validation and testing.

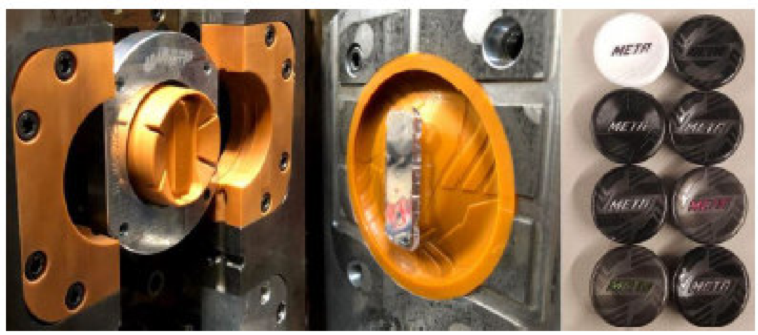


Fig. 17. 3D-printed tooling inserts in orange (left and center) and injection-molded parts (right), courtesy of DeMarini Sports and Fortify

AM also supports the inclusion of conformal cooling channels in tooling. These channels follow the shape of the cavity to better remove heat from a tool than straight drilled channels. The result is shorter molding cycle times, extended tool life, and better part quality. The following image shows complex conformal-cooling channels, which could only be created by AM.

Fig. 18. 3D-printed part with conformal cooling channels, courtesy of 3D Systems

AM can also be used to produce other types of tools, including jigs, fixtures, templates, gauges, and drilling and cutting guides. These tools are typically geometrically complex and made in low quantities, making AM a good fit. This type of tooling can be expensive and time consuming to produce using conventional methods. Medical cutting and drilling guides follow organic contours and are difficult to produce economically using conventional manufacturing.

Fig. 19. Custom AM dental implant drill guide, courtesy of Think3D

AM is also used to produce patterns for metal investment casting. This process eliminates the need to manufacture expensive and time-consuming wax pattern tooling. Several AM materials can be melted or burned out of a ceramic and stucco shell for investment casting. VPP and MJT processes have become a staple in the jewelry industry for this application.

Fig. 20. 3D-printed wax pattern being attached to an investment casting tree (left) and final metal necklace (right), courtesy of Sergio Zenere and DWS Systems

BJT can produce molds and cores for sand casting. The following image shows a large 3D-printed sand mold. Metal-casting processes are explained in detail in the Cast Metal Parts supplemental document at wohlersassociates.com/castmetal2023.pdf.

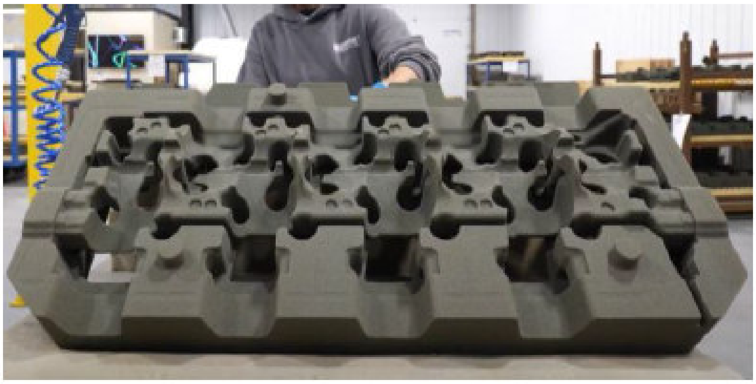


Fig. 21. 3D-printed sand core for large metal casting, courtesy of Hoosier Pattern

Final part production

One of the most interesting applications of AM is producing end-use parts. It represents 30.5% of all AM applications, based on research by Wohlers Associates. AM can be used for short-run production using polymers, composites, metals, ceramics, and biomaterials.

Consumer products include eyewear, footwear, and many other products. The following image shows a pair of eyeglass frames 3D printed in titanium. Today, most 3D-printed consumer products are more expensive than their conventionally manufactured counterparts, but added functionality, performance, and/or features can justify the price.

Fig. 22. 3D-printed titanium eyeglass frames, courtesy of Hoet

The production of parts for footwear is a popular application. The following image shows custom insoles produced by Podoactiva of Spain. The company uses a clinical approach to capturing data from a customer, compared to some competitive companies, before production begins. The insoles are produced using a mix of materials and methods that include HP multi jet fusion and conventional manufacturing.

Fig. 23. Custom insoles, courtesy of Podoactiva

The following part is a 3D-printed brake rotor for the Dodge Challenger Hellcat created by Ceramic Disc Technology. The company uses lattice structures to optimize performance. The rotor weight was reduced by 62%, coupled with a fivefold thermal conductivity improvement compared to a standard cast-iron brake rotor.

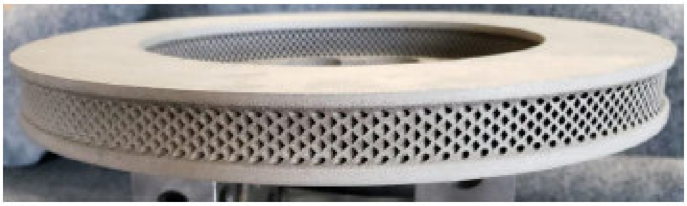


Fig. 24. Ceramic-aluminum brake rotor before finishing, courtesy of Ceramic Disc Technology

Additional applications

Exciting and unanticipated applications of AM are appearing regularly. NASA and the European Space Agency have successfully tested the making of parts by MEX on the International Space Station. They are also investigating the use of metal AM in space.

Several 3D printers for candy and vegetarian protein alternatives have been on the market for years. 3D bioprinting has been a research topic for more than 25 years, but it has been slow in transitioning to the commercial sector.

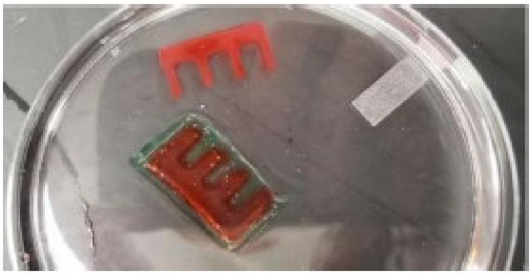


Fig. 25. Collagen (red) and polymer mold (green) created with AM, courtesy of Advanced Solutions

The following image shows a portable toilet dubbed by its creators as The Throne. The structure and sliding door were 3D printed from recycled plastics. One of the portable toilets was produced and used at a construction site.

Fig. 26. 3D-printed porta potty, courtesy of To.org and Nagami

Many more examples of final part production are found in Part 4 and other places throughout this report.

Industries

Companies were asked to indicate which industries they serve and the approximate revenues (as a percentage) they receive from each. (See the previous section titled "Industry survey" for details on the companies that received the questionnaire and their locations.) The following graph shows the results.

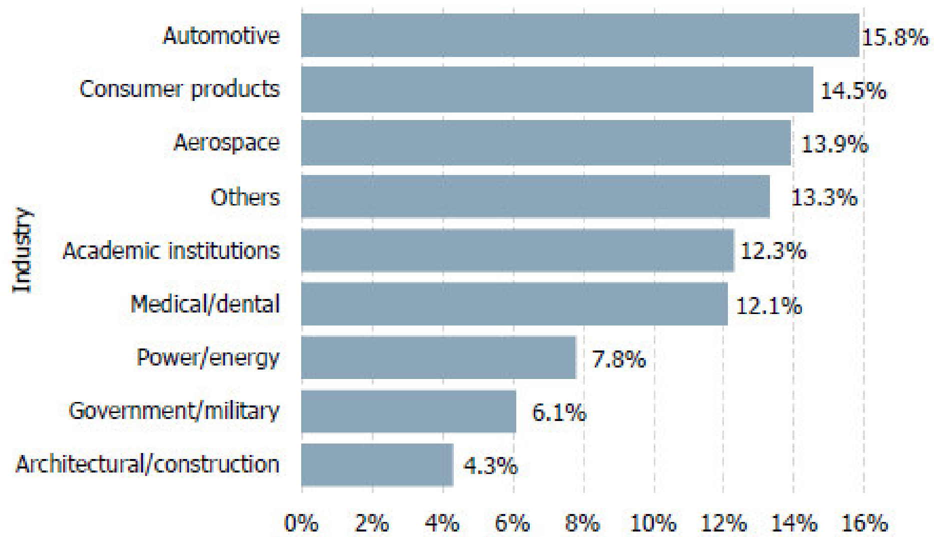


Fig. 27. Revenue percentages by industry; source: Wohlers Associates

The following industries have been using AM for varying amounts of time. These examples show the many ways that AM technology is impacting industry, from aerospace to fashion.

Aerospace

The aerospace industry was one of the earliest adopters of AM. The technology, especially when design for additive manufacturing (DfAM) is applied, can create lightweight parts, resulting in a reduction in weight, fuel consumption, and emissions. The industry uses AM for many applications, including prototyping, repair, maintenance, tooling, and research and development. Increasingly, it is being used for the production of flight-critical parts.

As AM advances, so do the types of aerospace applications it benefits. Airbus recently selected Avio Aero's Catalyst engine to power its Eurodrone unmanned aerial system (UAS). The company claims the engine is the first aerospace turboprop with 3D-printed parts. The use of 3D printing reduced 855 parts to just 12 and weight by 45 kg (99 lbs). Also, it improved fuel burn by 20% and power by 10%.

Fig. 28. Eurodrone UAS, courtesy of Airbus

German aircraft production and maintenance company Lufthansa Technik has produced 3D-printed aircraft parts for years. Most of them are polymer air ducts and fasteners used within the aircraft cabin.

In June 2022, aircraft parts supplier Premium AEROTEC designed and manufactured a metal load-bearing component for Lufthansa Technik. The titanium part, called an A-Link, is being used in the engine anti-icing system of the IAE-V2500 engine. The European Union Aviation Safety Agency granted the A-Link official aviation certification in 2022.

Fig. 29. 3D-printed titanium A-Link, courtesy of Premium AEROTEC

Airbus has included AM parts in its aerospace vehicles for several years. In 2022, the Advanced Center for Aerospace Technologies (CATEC) produced the first AM structural parts to fly in an Airbus helicopter. The parts are titanium fittings for the moving surfaces of the helicopter's tail. CATEC 3D printed several additional parts to attach cameras and antennas to the helicopter.

AM is also used to produce parts for rocket engines. In 2022, Ursa Major, a company focused on rocket propulsion, introduced the largely 3D-printed Arroway engine. The liquid oxygen and methane staged combustion engine has more than 889,644 N (200,000 lbs) of thrust. The reusable engine is available for order and scheduled for initial hot-fire testing in 2023 and delivery in 2025.

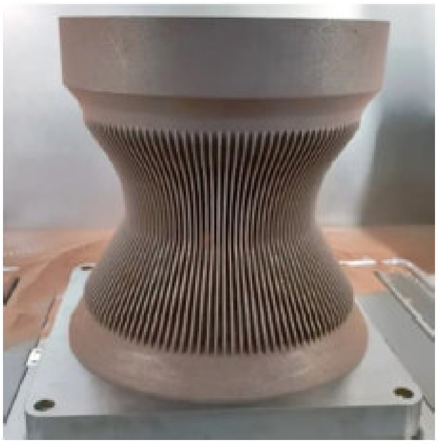


Fig. 30. 3D-printed copper section of Arroway's main combustion chamber, courtesy of Ursa Major

Relativity Space, a California aerospace startup, is working to 3D print an entire rocket, including the fuselage, engines, and fuel tanks. The company has designed a proprietary large-scale DED system called Stargate. The co-founder and CEO, Tim Ellis, said the company had designed a new version of the Stargate system that can print 10 times faster than its predecessor. The rocket has a payload capacity of 1,250 kg (2,755 lbs) to low-earth orbit.

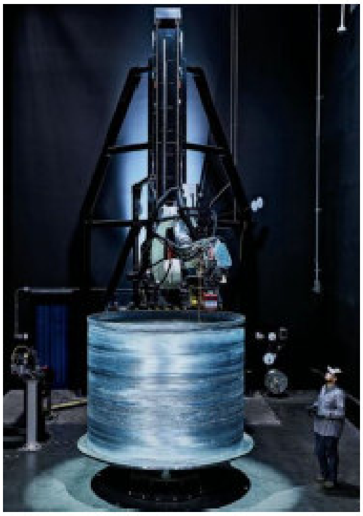


Fig. 31. Stargate DED system printing the Terran 1 fuselage, courtesy of Relativity Space

In addition to producing new aerospace parts, AM can also repair worn or damaged parts. GE Aviation Engine Services Singapore became the first maintenance, repair, and overhaul facility approved to use metal AM for commercial jet engine component repairs. The repair of high-pressure compressor blades is an example of a part that can benefit from AM. These blades run at high speeds in aircraft engines, have tight tolerances, and require regular repairs. GE Aerospace has developed an automated AM process to repair the blade tips, which has replaced a time-consuming machining process used previously.

Many aerospace parts are subject to extreme temperatures and environments. A single part can even have multiple temperature requirements for its different sections. One example is a rocket nozzle, which has different working temperatures and heat flow in its upper and lower regions. To address this issue, AM supports the use of gradient and multiple materials within a single part.

InssTek, a South Korean metal DED technology developer, manufactured a rocket nozzle using two functionally graded metals in a single build. The combination of aluminum-bronze alloy and stainless steel created a stable, strong part that the company claims can withstand harsher conditions than previous designs.

Fig. 32. Rocket nozzle using functionally graded metals, courtesy of InssTek

Satellites are also benefiting from AM. Fleet Space, an Australian company, is manufacturing what is expected to be the first fully 3D-printed satellite. The Alpha satellite is scheduled to be launched into low-earth orbit by SpaceX in 2023. The satellite design includes radiation shielding manufactured using Titomic's cold spray AM and coating process, which deposits and fuses dissimilar materials. Titomic uses a technology called Kinetic Fusion to create shielding that mitigates ionizing radiation and prolongs the satellite's life.

Medical

by Andy Christensen and Nicole Wake

Every human body is different, yet most medical devices are currently made in standard sizes. AM offers new methods and possibilities in medical device design and production. Medical applications of AM continue to develop and grow, particularly for personalized batches and complex designs. As a result, medical applications of AM are widespread in hospitals and the medical device industry.

Hospital- and clinic-based manufacturing, also called point-of-care (POC) manufacturing, is developing rapidly. With POC manufacturing, hospitals and individual physicians produce patient-matched devices. Typically, it occurs in a hospital or at a physician's office. AM plays a key role in POC manufacturing because of its inherent capability of producing highly personalized products.

Fig. 33. Collaboration at POC between surgeon and radiologist using anatomic models for surgical planning, courtesy of the Mayo Clinic

Patient-specific AM applications include anatomical modeling, virtual surgical planning and templating, and implants. 3D-printed anatomical modeling has proved beneficial and has been shown to positively impact patient care for many clinical applications, including craniomaxillofacial, orthopedic, cardiovascular, and urologic surgery.

Fig. 34. Anatomical model produced using BJT showing distal femur (white) with growth plate (yellow), tumor (purple lattice), nerve (green), vein (blue), and artery (red), courtesy of Nicole Wake

Patient-specific, physical anatomical models are produced after converting volumetric medical imaging data into a suitable 3D-printing file format (e.g., STL or OBJ). The imaging data can come from computed tomography or magnetic resonance imaging.

3D-printed anatomical models are typically created at full scale and used by surgeons before and during surgery. According to surgeons, these models:

- Support better visualization of complex anatomy before surgery
- Help to prepare and refine surgical plans
- Permit physical simulation of a surgical procedure on a model
- Give more confidence to a surgical team
- Provide a reference guide during surgery to understand anatomy and aid doctors during a surgical procedure
- Offer a visual aid to a patient and family for increased understanding of anatomy and disease, thereby improving informed consent for surgical procedures
- Support the teaching of residents, fellows, and medical students

Fig. 35. Heart surgeon reviews a multi-color model of a child's heart before going into the operating room, courtesy of Rady Children's Hospital

Virtual surgical planning and templating is an important application of AM. Using medical images, accurate surgical planning can be performed virtually before a plan is executed in the operating room. Surgical guides, templates, and models can be designed and produced by AM based on the plan. This technique is commonly used for corrective osteotomies, replacing a removed tumor with a "graft," and total joint replacements.

Fig. 36. 3D-printed surgical guides (white) with other surgical tools, courtesy of Materialise

Fig. 37. 3D-printed surgical guide being used in surgery, courtesy of Materialise

3D-printed anatomical models have supported the production of patient-matched implants for more than 20 years. These cases involved designing a patient-specific implant based on medical imaging data. Today, devices are designed in a digital environment. An implant can be produced using AM or conventional manufacturing, with associated fixtures, molds, and jigs often made by 3D printing. Common applications for personalized implants include:

- Neurological surgery—creating a cranioplasty implant to replace missing bone in the skull
- Plastic and reconstructive surgery—implants to augment the shape of the face or body, typically made from polymers and silicones
- Oral and maxillofacial surgery—personalized titanium plates used following surgery to hold bony segments in a pre-determined shape and patient-matched implants to replace the temporomandibular joint
- Orthopedic surgery—large, typically titanium implants used to replace missing portions of bone lost to trauma or a tumor

- Personalized titanium plates used to hold bony segments into a pre-determined shape and personalized total-knee-replacement implants for a relatively small percentage of the overall market

Orthopedic implants used today are made in standard sizes. They are typically made using traditional manufacturing such as machining, investment casting, and injection molding. However, a growing number of polymer and metal medical devices in serial production are being made using AM. As of February 2022, the Food and Drug Administration (FDA) had cleared more than 250 medical devices made by AM, according to a representative of the FDA's Additive Manufacturing Working Group.

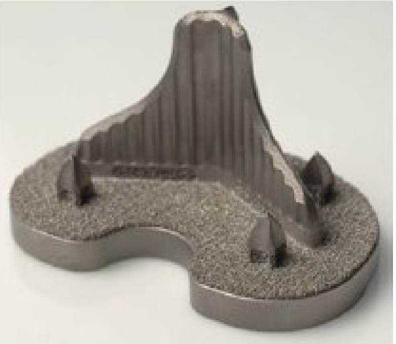


Fig. 38. Titanium tibial baseplate, courtesy of Stryker

The medical device industry uses AM for complex, porous metal structures that traditional manufacturing cannot create. These structures promote bone in-growth and are lightweight. They help with stress shielding, which is the improper transfer of a load from surrounding bone. AM is a more flexible method for manufacturing these parts. The most common applications for AM in serial implant production are:

- Spinal fusion devices (known as spinal cages)—produced in a titanium alloy or polyetherketoneketone (PEKK)
- Acetabular cups (known as hip cups)—produced in a titanium alloy (usually Ti-6Al-4V) and cobalt-chrome
- Tibial baseplates, which is the tibial portion of a total knee replacement—produced in a titanium alloy, with the bearing surface manufactured conventionally in polyethylene
- Gap-filling wedges for extremities—produced in a titanium alloy

AM can also be used to make personalized implants. It is an ideal technology for this application due to the ease of producing objects of high complexity. Personalized implants offer a host of potential benefits, such as faster surgeries and recoveries and improved bone preservation.

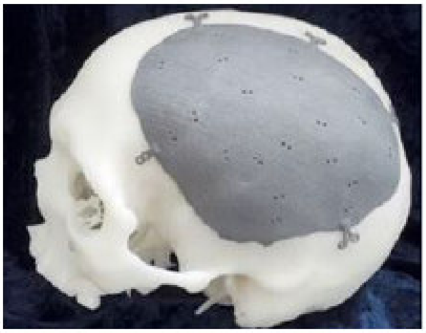



Fig. 39. Personalized titanium cranial implant (left) and personalized titanium acetabular implant, courtesy of Walter Reed National Military Medical Center and Materialise

Medical 3D printing is a disruptive technology. With continuously improving AM technologies and material developments, patient care is being impacted increasingly by AM.

Dentistry

The dental industry has increasingly adopted 3D printing for several different applications. Both dental offices and laboratories have taken advantage of the technology. Some of the most common applications for dental 3D printing include surgical guides, models, aligners, and implants.

The availability of AM has simplified traditional procedures such as creating orthodontic appliances. The scope for using AM has been broadened by the ease of collecting 3D data of a patient's oral anatomy using intraoral scans or radiological imaging. The data is used to create a 3D model as the basis for designing and 3D printing dental parts. A 3D-printed model also allows dental professionals to plan procedures or test fit devices such as aligners and retainers.

Like the rest of the healthcare industry, dentistry is using 3D printing to manufacture surgical guides. Patient-specific guides are placed in a patient's mouth to ensure the proper placement of an implant or drilled hole.

Fig. 40. 3D-printed surgical guide, courtesy of Formlabs

3D printing is also used to make patterns for casting crowns, bridges, and copings. Increasingly, however, copings, which are the basis for crowns and bridges, can be 3D printed directly using metal PBF. Cobalt-chrome is the most common metal used for copings. The material is also used for dental prosthetics, such as partial denture frames.

Fig. 41. Build plate with 3D-printed cobalt-chrome dental copings, courtesy of 3D Systems

Most metal AM systems used in dentistry are housed and operated by large dental labs or service centers that receive orders from smaller labs and clinics. Metal 3D printers are typically best suited to large production runs of dental products.

VPP is the most popular polymer AM technology in the dental industry, according to the Journal of Dental Sciences. Recent years have seen significant growth in the range and capabilities of VPP resins. Strong and rigid materials are used to 3D print complete dentures, which is faster and less expensive to reproduce when a replacement is needed.

One area in dentistry in which 3D printing is having a major impact is the production of dental aligners. Align Technology was the first company to commercialize clear plastic aligners as an alternative to traditional metal braces. Intraoral scan data is used to 3D print a series of patterns over which thin sheets of plastic are thermoformed to create the aligners. In 2022, Align was manufacturing in the range of 525,000 aligners per day, and a pattern was 3D printed for each of them.

Other companies, such as SmileDirectClub, are now competing with Align Technology. Graphy and LuxCreo have even begun to 3D print aligners directly using VPP.

Fig. 42. Clear plastic aligner, courtesy of Invisalign

An industry goal is the use of 3D printers in dental offices for "chairside" 3D printing. This idea becomes feasible as dental-specific desktop 3D printers become faster, more user-friendly, and affordable. Most dental practices wanting to take advantage of 3D printing send 3D digital models to labs for production. This results in wait times and requires that patients return to the dental office.

In February 2022, Desktop Health, the healthcare subsidiary of Desktop Metal, launched the Einstein 3D printer, a desktop VPP system designed for dental offices. Using the Einstein system, along with Desktop Health's FDA-cleared Flexcera Smile Ultra+ photopolymer, dentists can print crowns, bridges, veneers, inlays, and outlays while the patient waits.

Fig. 43. Partial 3D-printed crown, courtesy of Desktop Health

Automotive

The automotive industry has used AM for decades, initially for concept modeling and prototyping. Currently, automotive companies use AM for design validation, fit and function testing, and some types of tooling. The sector's use of AM for final part production is mostly limited to low production volumes for high-end vehicles.

General Motors has been using AM for more than 30 years. Recently, the company has begun using the technology for production parts. When engineers made a last-minute change to the 2022 Chevrolet Tahoe's design, a new spoiler closeout seal was needed. Creating the tooling for injection molding would have resulted in delivery delays to customers, so GM partnered with GKN Additive (Forecast 3D). Using HP multi jet fusion, GKN printed 60,000 seals in five weeks.

Fig. 44. 3D-printed closeout seal for the Chevrolet Tahoe, courtesy of GM

GM signaled its commitment to increasing its use of AM in 2021 by opening its 1,400 m^2 (15,000 ft^2) Additive Industrialization Center (AIC). The AIC is space dedicated to AM, which will help GM scale up its production of 3D-printed prototypes, tooling, and end-use parts.

Ford was also an early adopter of AM. In the late 1980s, the company purchased an SLA from 3D Systems and used it to prototype new designs. Ford now has a dedicated 3D printing lab, which includes a robot to help automate production. The wheeled robot, called Javier, was supplied by KUKA and operates Carbon 3D printers without human intervention. The automation increases throughput and reduces the cost of custom 3D-printed parts.

Fig. 45. Ford's Javier robot operates a Carbon 3D printer, courtesy of Ford

BMW's iX5 Hydrogen vehicle features many model-specific design elements produced by AM. Its front grill cover, air inlets, and rear trim were 3D-printed. Some of the parts were produced at BMW Group's Additive Manufacturing Campus in Oberschleissheim, Germany. As of December 2022, the BMW Group had printed 430,000 AM parts. Many are installed on production vehicles under the Rolls-Royce, BMW, and MINI brands.

Fig. 46. BMW iX5 Hydrogen (left) and MINI Clubman (right), featuring 3D-printed trim components, courtesy of the BMW Group

The automotive racing industry has been using AM to improve performance and efficiency of race cars. In 2022, NASCAR debuted its Next Gen car, which features a 3D-printed cockpit ventilation unit. The vent was printed on a Stratasys H350 machine and is said to be the first 3D-printed production part used widely on a NASCAR vehicle.

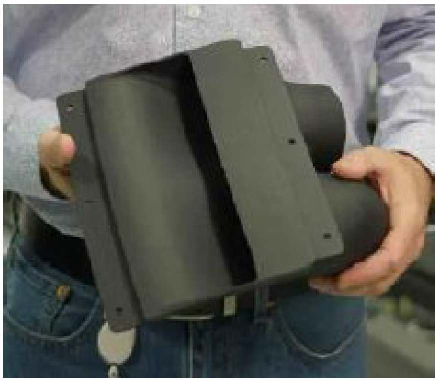


Fig. 47. Windshield-mounted cockpit ventilation unit, courtesy of Stratasys

In Italy, the Politecnico di Milano Dynamis PRC team designed a new single-seat electric race car using 3D printing. The team used the RadiciGroup Radilon Adline brand of filament to print an engine cable support and flap ribs for the car.

AM is sometimes used to reduce shipping costs. In 2022, Desktop Metal subsidiary Adaptive3D unveiled FreeFoam, a photopolymer containing heat-activated foaming agents. After printing, the material expands up to seven times its original size when heated in an oven. This allows the parts to be shipped in a compact package before expanding to the final size for assembly. FreeFoam is being positioned for the production of automobile seats and similar applications.

Fig. 48. Seat 3D printed in FreeFoam (left) and fully expanded version (right), courtesy of Desktop Metal

Bentley Motors invested £3 million ($3.6 million) to double the AM capacity at its Crewe, England headquarters. The company produced 15,000 3D-printed parts in 2021. The Volkswagen subsidiary has used AM to create prototypes, such as full-scale powertrain models and aerodynamic wind tunnel models, as well as production parts. The company plans to use its expanded AM capabilities to offer personalization options on its vehicles.

Australian AM system manufacturer SPEE3D has printed automotive parts for companies such as Nissan. SPEE3D printed a 9-kg (19.8-lb) racing wheel in 5.5 hours for the 2022 Melbourne F1 Grand Prix. The company's cold spray technology produces a near-net-shape part that requires machining to meet dimensional tolerances.

Fig. 49. 3D-printed wheel, courtesy of SPEE3D

Consumer products

Consumer products cover a wide range of goods such as eyewear, footwear, jewelry, and athletic equipment. A growing number of companies are using AM to produce consumer products. The technology can speed time to market, create unconventional shapes and geometric features, and support mass customization.

Smith is a manufacturer of goggles, helmets, sunglasses, and other products. In 2022, the company introduced the I/O MAG Imprint 3D Goggle for skiing and snowboarding. Customers use a simple phone app to 3D scan their faces and submit the data to Smith. This data is used to manufacture the polymer parts that make up the product's frame using multi jet fusion machines from HP. The customer selects the preferred lens and strap to complete an order. The price of the product is $450 and delivery is about two weeks.

Fig. 50. Custom ski goggle, courtesy of Smith

SILCA, a manufacturer of bicycle accessories, uses AM to create Chisela, a titanium computer and accessory mount. Its T-Tray mounting system was inspired by the T-shaped underfloor of a Formula One race car. Using AM, the company created a gyroid feature inside the form, which supports the load of the mount. The gyroid design makes the system lightweight but strong.

Fig. 51. 3D-printed Chisela bicycle accessory mount, courtesy of SILCA

3D printing has been a part of the fashion industry for many years. In May 2022, Stratasys launched the J850 TechStyle system. It uses the company's PolyJet technology to print directly onto textiles, including cotton, polyester, linen, denim, and leather.

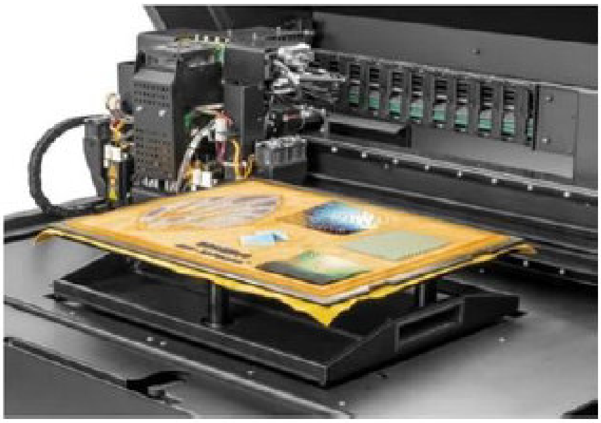


Fig. 52. J850 TechStyle 3D printer, courtesy of Stratasys

Many manufacturers are using 3D scanning and printing technology to create bespoke wearable products like custom-fit earbuds. In April 2022, Campfire Audio released a new line of custom earbuds. Impressions are first taken of a customer's ears and they are then 3D scanned. Once designed, the earbud housings are 3D printed. Campfire Audio claims this process results in better comfort and sound quality.

Fig. 53. 3D-printed Supermoon earbuds, courtesy of Campfire Audio

Sustainability is one reason companies have been turning to 3D printing. In January 2022, German company VAUDE released a backpack that can be recycled and used as feedstock for

AM. Textiles are usually difficult to recycle because many of them are made from multiple fabrics. The Novum 3D backpack, however, is made from a single TPU material and features a 3D-printed suspension system. The design uses a strong, lightweight honeycomb structure and is printed using technology from fellow German company OESCHLER.

Fig. 54. Novum 3D backpack, courtesy of VAUDE

A common thread in 3D-printed products is the use of unconventional structures such as lattices and honeycomb patterns. These structures are typically difficult or impossible to produce using other manufacturing methods. They are used where they benefit products by reducing weight and enhancing strength. This is the case with KAV Sports' Portola bicycle helmet introduced in April 2022. According to KAV Sports, the 3D-printed structures in the helmet increase protection in the case of an accident, while providing extra ventilation. The Portola helmet is also custom fit using a "fit kit" and virtual fit session to establish exact measurements.

Fig. 55. 3D-printed Portola helmet, courtesy of KAV Sports

Metal AM is used less frequently than polymer AM to produce consumer products. However, as metal AM becomes less expensive and more accessible, some consumer product manufacturers are turning to the technology. In 2022, metal AM company 3DEO printed the Era razor in stainless steel for Blackland Razor. According to Blackland, 3D printing was used to produce a design that would have been impossible to achieve with other methods of manufacturing.

Fig. 56. Era razor, courtesy of Blackland Razors

Education and academic research

AM has become a mainstay within education and research. Many universities, colleges, high schools, and middle schools have access to low-cost 3D printers for students. Educators are learning how to use AM to support science, technology, engineering, arts, and mathematics. Students can learn how to use simple CAD software and watch their parts being built. AM can provide physical models for students to better understand the real world.

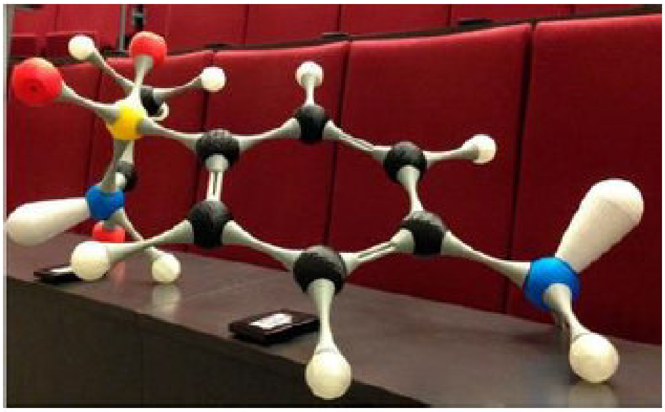


Fig. 57. Molecular models for organic chemistry lectures and exercises, courtesy of ACS Publications

At universities and national laboratories, AM is being used for R&D. Researchers at the University of Arizona are using 3D printing to make wearable sensors. One device was designed using a 3D scan of the area of the body where the sensor is to be fitted. The following image shows a sensor produced using AM with electronics embedded in the part for data collection.

Fig. 58. Wearable sensor, courtesy of Philipp Gutruf

Researchers at Stanford University and the University of North Carolina at Chapel Hill developed a 3D-printed patch to deliver vaccines. They claim the delivery system performs better, compared to conventional delivery methods. The patches were produced on a VPP system from Carbon.

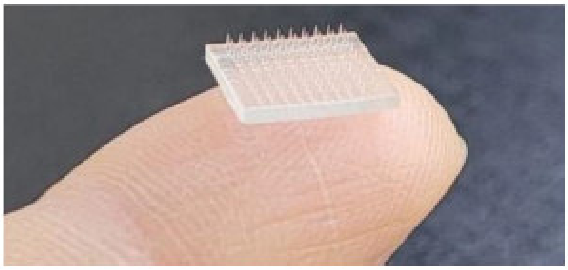


Fig. 59. Microneedle patch for delivering vaccines, courtesy of the University of North Carolina and Stanford University

GE Research has partnered with the University of California at Berkeley and the University of South Alabama. The partnership is focused on creating a system to capture carbon dioxide from the atmosphere. The work involves the development of a heat exchanger, shown in the following image. It is funded by a two-year, $2 million grant from the U.S. Department of Energy.

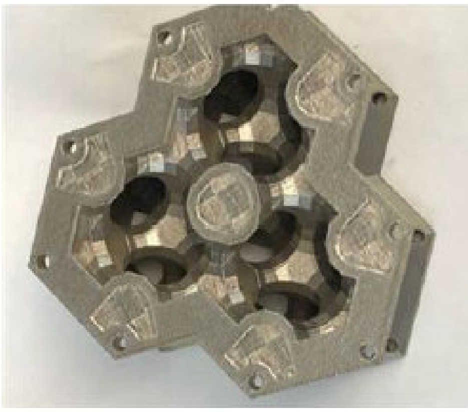


Fig. 60. Prototype heat exchanger made using metal AM, courtesy of GE Research

An extensive and detailed list of AM activities at academic institutions, national laboratories, and other groups can be found in Part 6 of this report.

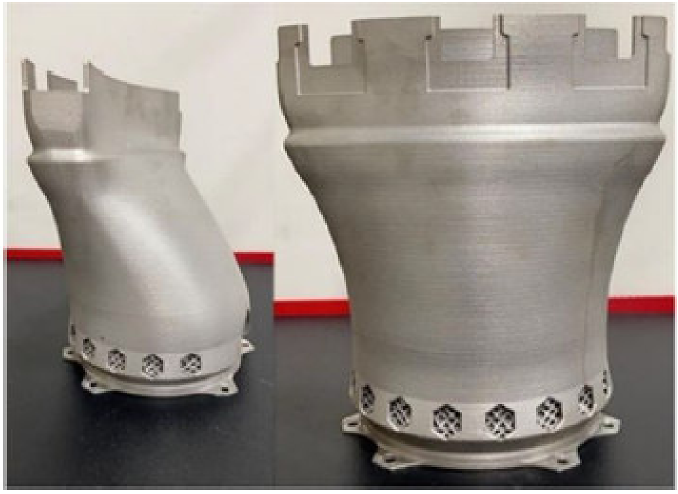
Power and energy

The power and energy sector includes oil and gas and renewable technologies such as wind and solar power. This sector has been using 3D printing for years for the repair of worn and broken parts and prototypes. As the industry pushes toward a greener future, AM is being used to improve renewable technologies such as wind turbines and batteries.

AM is appealing to many organizations within this industry because it can help reduce physical inventories, create lighter parts, and speed production. Many factors are being considered such as regulatory issues, volatility of oil and chemical processing, liability, and certification.

Companies in the power and energy sector are using AM to improve the strength of parts and reduce costs. The following image shows a part for a combustion system produced by Siemens Energy. The part was previously made by joining up to three parts. With 3D printing, the company manufactured the part in one piece, eliminating assembly steps and reducing cost. The part also features lattice structures between the inner and outer walls for improved thermal stress management and better fatigue life.

Fig. 61. Combustion system part, courtesy of Siemens Energy



GE Renewable Energy is using AM to make wind turbines more efficient, less costly, and easier to build. The taller a wind turbine, the more energy it can harness. Transporting the parts for a large tower to an installation site, however, is challenging and costly. GE Renewable Energy aims to address this issue by 3D printing the base of a tower on-site using cement-based additive systems.

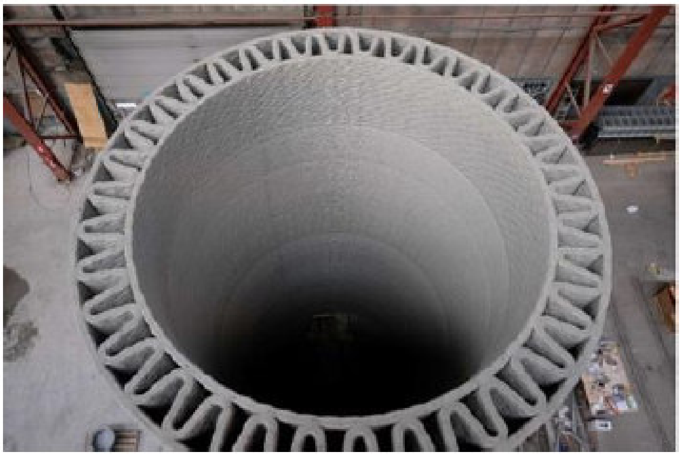


Fig. 62. Section of a 3D-printed wind turbine tower, courtesy of GE Renewable Energy

The power and energy industry is also benefiting from using AM for spare parts. In May 2022, Brazilian oil and gas solutions company Ocyan introduced AM to its spare parts supply chain for the first time. Ocyan partnered with French company Spare Parts 3D, which offers the DigiPART software for analyzing whether parts are a good fit for AM. In 11 weeks, the team analyzed 17,000 spare parts from Ocyan's inventory and identified 11% of them as viable for production by AM.

Shell is also taking advantage of AM to keep a digital inventory. In May 2022, the company began operating 3D-printed impellers for a centrifugal pump at the Shell Energy and Chemicals Park in Rotterdam, Netherlands. The spare parts were deployed in collaboration with Baker Hughes. By 3D printing the parts, Shell reduced the time, cost, and waste associated with storing physical spare parts.

Fig. 63. Centrifugal pump rotor with 3D-printed impellers, courtesy of Shell

Renewable energy has its own environmental and cost challenges. The manufacture of lithium-ion batteries is expensive and involves environmentally harmful mining practices. Scientists at the University of California, Los Angeles and Lawrence Livermore National Laboratory received a $900,000 grant from the U.S. Department of Energy in August 2022. The funds are being used to develop 3D-printed lithium-ion batteries. The goal is to increase power, which is said to speed charging, reduce material waste, and decrease cost.

Government and military

Globally, governments and branches of the military are investing in AM research, education, and infrastructure. Government and military applications typically involve relatively low volumes of parts. Interest in AM is driven by the need for less costly spare parts, reduced lead times, custom product design, and personalization.

In May 2022, U.S. President Joe Biden announced the AM Forward program. The initiative aims to strengthen supply chains and create more U.S.-manufactured products through an investment in AM. Seven large manufacturers signed on as initial participants in the plan. These manufacturers have agreed to provide support for their smaller, U.S.-based suppliers to assist in their adoption of AM.

The U.S. Department of Defense, in partnership with the private sector, is building three military barracks using additive construction technology. At 530 m^2 (5,700 ft^2) each, the barracks are said to be the largest 3D-printed structures in the Americas. They will also be the first 3D-printed structures to comply with the Department of Defense's newly released Unified Facilities criteria for additive construction.

In 2022, soldiers on Ukrainian battlefields were aided in different ways by 3D printing. Companies such as 3D Tech Additive and others in the 3D printing community used the technology to fabricate items needed in the field. They included everything from medical supplies to replacement parts and weapon accessories.

Fig. 64. 3D-printed parts for a tourniquet, courtesy of Jakub Kaminski

In October 2022, the U.S. and UK militaries partnered for Project Convergence 22. The collaboration was formed to apply advanced manufacturing technologies, such as 3D printing, in operational environments. The project's goals are to support those in the field with repairs on location and on demand.

Also in 2022, the U.S. Navy tested, for the first time, the viability of metal AM at sea. The U.S.S. Essex was the first U.S. Navy ship to install a 3D printer aboard in 2014. In 2022, it used Xerox's ElemX metal AM system to make parts at sea.

Architectural models

by Charles Overy

The architectural and construction industry recorded strong growth in 2022. A shortage of skilled labor is driving demand for improved efficiency and proven innovation. Also, most young architectural professionals have studied 3D printing, with access to 3D printers.

In this environment, the production of architectural and other scaled models is a natural fit for AM. However, architecture has different requirements when compared to manufacturing and other industrial AM applications. Architectural models, like other visual prototypes, need to be aesthetically pleasing. The parts are often relatively large, with the largest dimension typically being greater than 350 mm (13.8 in).

Architectural models often have many distinct and separate surfaces with varying materials. A high level of detail and a smooth surface finish are critical features. It is also difficult to create complete models without large overhangs. Thin walls and long, unsupported features are common. These requirements dictate which AM technologies are the best for producing architectural models.

Low-cost desktop MEX machines and smaller digital light processing (DLP)-based VPP systems can be a useful starting point for companies wishing to produce 3D-printed scale models. They provide an understanding of the workflow and how AM can meet challenges. However, these machines are unlikely to provide the quality and capacity required for substantial commercial applications. Many companies that initially purchased low-cost MEX and VPP platforms are now replacing them with new-generation systems.

When selecting a low-cost machine, it is important to understand that some means of removing support material from overhanging features is necessary. Dual-extruder systems offering soluble supports are particularly useful. Purchasers of MEX technology should look for a high-speed machine with a small nozzle and one that offers excellent machine mechanics. They should avoid large-format MEX platforms if they are not rigid or offer large-diameter nozzles and/or thick layers.

VPP systems are generally a good choice for architectural models. High detail, low cost, and large build volumes are desirable. Large numbers of support structures are used in VPP, which can create significant labor and part quality issues. Large-vat, top-imaging VPP machines typically provide the highest quality parts but at a greater cost.

Powder-based systems typically remove the requirement for supports. PBF systems are rarely used because of the relatively high cost for large parts and possible warping from thermal stresses. BJT technology is a particularly good fit for many concept modeling applications because of relatively low costs and larger build volumes.

Full-color AM systems have been used for architectural models since the early 2000s. Mimaki has two sizes of color MJT systems, which compete with mature systems from Stratasys. The lower cost of the smaller platforms from these vendors supports more experimentation and innovation. Despite poor material properties, the ProJet CJP machines from 3D Systems remain the color standard for architecture due to high speed and low part cost.

Successful implementation of AM for scaled models includes an understanding of the unique geometry processing challenges. Buildings are assemblies of thousands of parts. Scaled-down CAD data can result in thin-walled sections, which are prone to failure. Removing the interior of a CAD model to facilitate an exterior-only scale model is a complex task. A combination of these factors often makes it difficult and costly to generate data that will ensure good 3D printing results. It also requires special workflows and software.

Visualization of complex structures at scale will remain a viable but niche application in the broader AM market. The requirements for successful implementation are challenging but achievable. When selecting a system, consider cost and quality, with an appreciation of the unique requirements of architectural models. Understanding and planning for the costs of data preparation are key to successful implementation.

Additive construction

by Stephan Mansour

Additive construction (AC)—also called 3D-printed construction—is the application of AM to projects in the construction industry. The technology has seen increased activity in the past few years, with a proliferation of dedicated systems and services. The scope of AC projects is advancing with companies producing multi-story structures and large-scale 3D printing.

In November 2022, Dar Al Arkan, a property developer in Saudi Arabia, 3D printed the walls of a villa in Riyadh, Saudi Arabia. The villa measures 9.9 m (32.5 ft) in height and 345 m^2 (3,714 ft^2). PERI 3D Construction, in collaboration with HANNAH and CIVE, is constructing a 372-m^2 (4,000-ft^2) two-story, single-family home in Texas. The project uses a hybrid construction method that integrates cement-based 3D printing and wood framing.

Nidus3D of Kingston, Canada has printed the walls for two multi-family houses comprising a basement plus two upper floors. Each unit has 812 m^2 (8,740 ft^2) of living space.

ICON, in collaboration with major developer Lennar and Bjarke Ingels Group (BIG), deployed a fleet of 3D printers to print the walls of 100 homes in Texas. The three- and four-bedroom homes are offered with eight different floor plans and 24 unique exterior designs. They range in size from 139 m^2 (1,500 ft^2) to more than 195 m^2 (2,100 ft^2).

Fig. 65. ICON's Wolf Ranch project in collaboration with Lennar and BIG, courtesy of ICON

Irish firm Harcourt Technologies is planning to 3D print the walls of 46 "eco-homes" for the Building for Humanity organization in Lancashire, UK. The homes will provide housing for the homeless and low-income families.

It is unclear whether the printing of straight walls can be justified on an economic basis. The cost of wood framed walls in residential homes is in the range of 5% of the total cost. Even if this cost was halved, it would not "move the needle" much. One also needs to consider the running of electrical, plumbing, and air conditioning and heating through or along concrete walls. The fitting of doors, windows, cabinets, and other structures can be more difficult with concrete, compared to wood framed walls. Finishing the inside and outside of concrete walls is another consideration.

Fig. 66. Building for Humanity's proposed eco-home project, courtesy of Harcourt Technologies

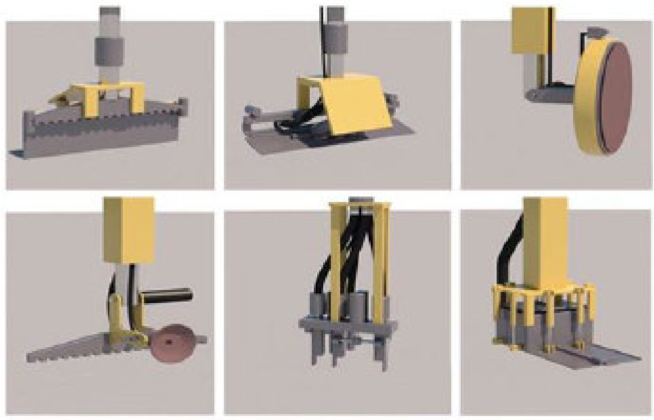
Standards are a critical enabler for the AC sector. After a year and a half of intense collaboration with international subject matter experts, authorities, and professionals, ISO/ASTM 52939 was made public in November 2022. The standard went through a second and final review process before official publication in early 2023. It outlines the requirements necessary for production and delivery of high-quality additively constructed structures for residential or infrastructure applications. This global effort is timely because it supports several government-led initiatives such as the European Commission proposal COM (2022)144, published in March 2022. AC is explicitly addressed in the proposal. The European Committee for Standardization (CEN) has provisionally approved the adoption of ISO/ASTM 52939 once it has been published.

Increased activity in AC has driven further optimization and improvement. PERI 3D Construction implemented a rail system for its COBOD printer to facilitate repositioning for larger projects.

PERI has also included sensor technology to monitor the consistency of the material mixing ratio. Others are working to integrate locally sourced materials and improved material delivery subsystems.

EVOCONS has developed a unique system that includes several aspects of construction and not only the 3D printing of walls. The system works on a project's foundation, walls, grouting, tiling, and finishing. All functions are managed through a single machine and software platform. The company is seeking investment to produce the system commercially. Diamond Age is also integrating several functions in its robotic system.

Fig. 67. EvoConstructor toolkits, courtesy of EVOCONS



The environment is a relevant consideration with AC. Mighty Buildings claims to offer a zero-net-energy home with its use of recycled polymers and glass-fiber reinforcement. A two-bedroom, two-bathroom, 109-m^2 (1,171-ft^2) home is the first of 40 units to be built in a Southern California community.

Fig. 68. Mighty House Quatro, courtesy of Mighty Buildings

WASP's Itaca project is based on a concept of a 33-m (108-ft) diameter area enough to sustain a typical family of four. Constructed from locally sourced earthen materials, such as clay or mud, the house is to be part of an "off-the-grid" solution. It is not connected to electricity, gas, water, or sewer services. Itaca uses an array of technologies to create a circular micro-economy while maintaining environmental balance.

Fig. 69. Self-sufficient, sustainable structure made using AC, courtesy of WASP

In November 2022, the University of Maine's Advanced Structures and Composites Center (ASCC) unveiled BioHome3D. The 5.6-m^2 (60-ft^2) prototype features 3D-printed floors, walls, and roof, all made from wood fibers and bio-resins. The house is fully recyclable with 100% wood insulation. It is also equipped with sensors to monitor performance as it is exposed to cold, heat, snow, and humidity.

Fig. 70. BioHome3D, courtesy of the University of Maine ASCC

In December 2022, *Wohlers Specialty Report on Construction: Building an Additive Construction Future*, was published. The report details the history, current state, and future of AM in construction. It provides the landscape and key players in AC. In the months following the publication of the report, a list of 199 key players in the report has expanded. The report is available at wohlersassociates.com/construction2022.

Other industries

Other industrial sectors are also using AM. They include art, fashion, and entertainment. These industries use AM to speed production and to create unconventional items that would be difficult to make using other methods.

3D printing has been used in the fashion industry for years. It has been steadily evolving to support the design and production of new types of garments and accessories. In the following image, features were added directly to fabric using a J850 TechStyle system from Stratasys. Users of the system can create rigid or flexible garments with complex designs and optical illusions.

Fig. 71. Kimono created by Ganit Goldstein using the Stratasys J850 TechStyle 3D printer, courtesy of Stratasys

3D printing is used for custom products in many industries, including toys. Several companies have introduced the concept of the 3D-printed selfie. Customers can 3D scan their faces, often using nothing more than a phone. The scans are sent to a manufacturer who then creates a 3D-printed personalized figurine. The following image is from the Hasbro Selfie Series that allows customers to create 3D-printed action figures of themselves.

Fig. 72. Personalized 3D-printed figures from Hasbro's Selfie Series, courtesy of Formlabs

AM is also being used on a larger scale in novel ways. In June 2022, pool company San Juan Pools unveiled what it claims to be the first fiberglass swimming pool made by AM. The pool was printed on a system from Alpha Additive using recycled materials.

Fig. 73. 3D-printed pool, courtesy of San Juan Pools

The film and television industry uses AM to produce props and prosthetics. Dreamsmith Studio used a Form3L printer from Formlabs for the second season of its TV show *Raised by Wolves*. The printer was used to create masks, prosthetic makeup molds, and replicas of actors' bodies.

Fig. 74. Prosthetic makeup molds printed on a Form3L machine, courtesy of Dreamsmith Studio and Formlabs

AM is being used in nearly every industry, as the previous examples show. New applications of the technology are being developed regularly. They range from medicine and art to aerospace and sporting goods. The use of AM in these and other industries will continue to develop as the technology improves. AM technology itself is used to conceive and experiment with new ideas, helping to make them a reality.

Myths and misconceptions

In the history of AM, many myths, misconceptions, and untruths have been shared in writing, at events, and in conversations. The following are among those continuing to be shared and believed by some. Not all are myths, but rather a misunderstanding of the technology, process, or application.

AM will replace conventional manufacturing

Some have suggested that most products will be made by AM in the future. The cost of producing AM parts will decline in the coming years. However, it will likely remain a more expensive option for producing parts in high quantities. This will especially be true for low-value products with simple shapes and features. The layer-by-layer nature of AM makes it relatively slow, which contributes greatly to the cost.

Among the experienced, 3D printing is seen as complementary to conventional manufacturing. Certain parts can be produced with AM that are difficult, more expensive, or impossible to produce using conventional manufacturing. They include extraordinarily complex shapes, and structures using less material, resulting in lightweight parts. In some cases, unique microstructural features are possible with AM.

It is possible to produce custom products affordably with AM, especially those that would be too expensive using conventional methods of manufacturing. Often, the most cost-competitive process for metal part production is casting or computer numerical control (CNC) machining.

The guitar body in the following image would be impossible to create in a single piece using conventional manufacturing. However, the neck, bridge, pickups, tuning heads, and controls of the guitar are made conventionally.

Fig. 75. 3D-printed guitar body and conventionally manufactured parts, courtesy of Olaf Diegel

Complexity is free

For years, many have claimed AM offers "complexity for free." It is true that building parts layer-by-layer is largely independent of part complexity, but other elements of the start-to-finish process are not. For example, it takes more time, talent, and effort to create a complex design compared to a simple one, which adds cost. It can be difficult and costly to remove support material, finish surfaces, and inspect AM parts with complex features. Certain blind features are difficult or impossible to inspect, even with advanced methods such as computed tomography (CT) imaging.

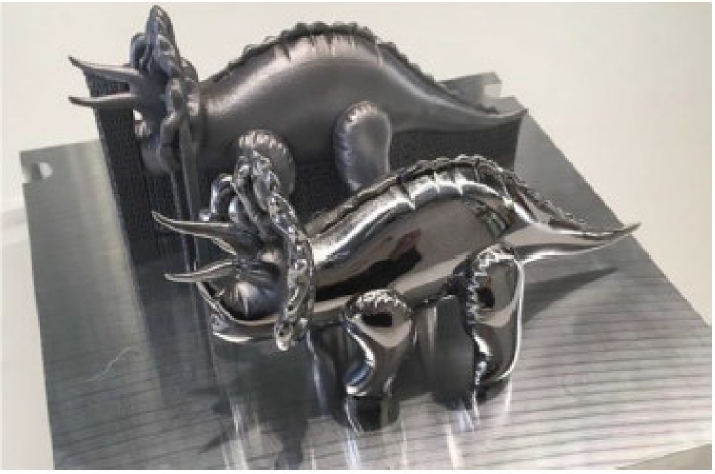


Fig. 76. Metal AM part before support material is removed (rear) and after support removal and polishing (front), courtesy of Gregor Kregar

Geometrically complex part production made possible with AM comes with many potential benefits. For example, designers can consolidate two or more parts into one. Some companies have digitally consolidated more than 100 parts into one and then printed the single part successfully. This eliminates part numbers, manufacturing processes, inventory, assembly labor, maintenance, and inspection.

Topology optimization can reduce material and weight and often results in a shape that can only be produced affordably on an AM system. Lattice and mesh structures can further reduce weight and improve product performance.

Fig. 77. Variable gyroid copper heatsink produced using AM, courtesy of CDAM Lab

AM is a "push-button" process

Many believe AM is a completely automated, push-button operation. One simply clicks "start" and returns later to find a finished product. Building high-quality polymer parts typically requires a significant amount of talent, effort, and labor, and metal parts can require even more. This includes generating the solid model, planning the process, adding and adjusting support material, and finishing the surface.

Building acceptable AM parts starts with a good design. Build orientation and nesting multiple parts in the build volume are also key. Both can have a considerable impact on the surface quality and build time. Planning is key, but it can occur only after one has sufficient knowledge and experience. This ensures that the best decisions are made when designing and preparing parts for AM.

Many pre- and post-processing tasks involve hands-on experience and skill. When preparing a build, it is important to determine the best orientation of the parts. Decisions about the type and placement of support structures and anchors are also important. Using the right machine build parameters contributes to part quality. Different operators will often produce parts with different results, even when using the same machine and material, because of the many variables involved. Idiosyncrasies between two units of the same model of AM system often cause troublesome variation in print results.

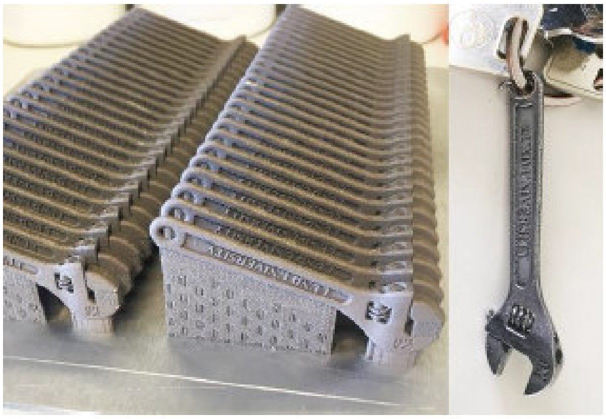


Fig. 78. Metal parts with support material still attached (left) and after manual removal and finishing (right), courtesy of Lund University

Most AM systems are similar

AM machines range in price from about $200 to more than $2 million. Build volumes span from smaller than the tip of an ink pen to the size of a house or larger. Specific processes, energy sources, and types and forms of materials are also wide-ranging.

Countless news stories, Hollywood films, and personal conversations have portrayed low-cost 3D printers as being capable of producing high-end, production-quality parts. Generally, this is not true. A wide gap in speed and quality remains between low-cost desktop 3D printers and high-end AM systems for large, complex parts.

Desktop 3D printers are incredibly valuable tools for creating, testing, and iterating new ideas. Nearly every engineer or designer should have a desktop 3D printer near them. However, they should also have access to industrial AM machines when projects can benefit from them.

AM is environmentally friendly

Good arguments for the sustainability of AM consider the entire lifecycle of the parts being produced. Sustainability has several components, including 1) energy consumed, 2) water requirements, and 3) carbon footprint. Sources of AM energy consumption include feedstock creation, operation of the AM system, post-processing, recycling, and scrap. Other energy considerations include potential savings while a part is in service and its end-of-life disposal.

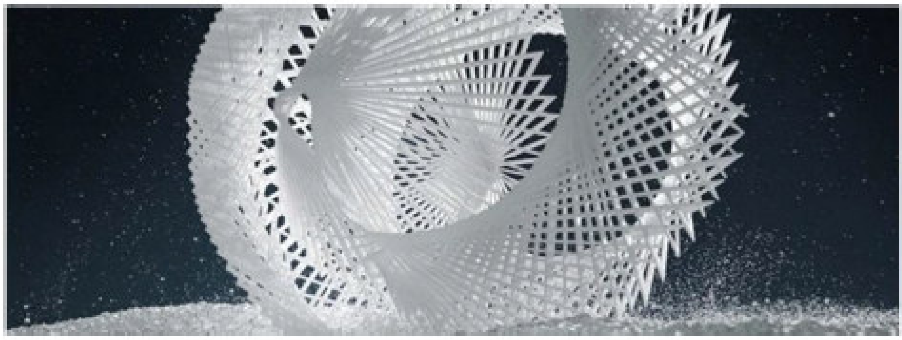
In general, the AM build cycle itself is not energy efficient compared to conventional manufacturing processes. This applies particularly to PBF, DED, and MEX. Power sources such as heaters and lasers are not energy efficient. Build rates are typically slow, so a significant amount of energy is consumed while creating a relatively small volume of parts. Energy consumption in manufacturing is typically normalized by the mass of a part. In comparison, machining consumes a fraction of the energy of a typical AM process. Conventional manufacturing processes, such as injection molding, forging, and casting, are typically more energy-efficient than AM. This is true even when considering the energy used to produce tooling needed for conventional manufacturing.

AM feedstock may not be fully recyclable. For polymer PBF, 20–40% or more of the powder may not be recyclable, depending on the specific material and refresh rate. Some metal powder may not be recycled if manufactured according to certain standards. Support material and post-process machining produce scrap, which represents an energy loss due to the embodied energy of feedstock creation and processing.

Water resources and the carbon footprint of AM are other elements of sustainability. Most AM processes, like many conventional manufacturing processes, use recirculated water for cooling. The carbon footprint is largely tied to energy consumption during part manufacturing and the source of energy (e.g., solar, fossil fuel, nuclear, etc.). Except for energy consumption, these factors are generally similar between AM and conventional manufacturing.

The case for sustainability in AM typically arises in 1) low-embodied-energy feedstock, 2) in-service energy savings, and 3) end-of-life part reclamation. Certain materials, such as wood and stone, have low embodied energy of production. They may be processed by AM, but typically with binding agents. Some companies are developing low-embodied-energy polymers. For example, new PA11 powders are now available for PBF that are made from 100% renewable castor beans rather than petrochemicals.

Fig. 79. Part made from castor-bean-derived PA11, courtesy of EOS



The energy savings of a part while in service can have a large impact. For example, a topology-optimized AM part that weighs less than a conventionally manufactured part can consume less energy in service if it is transported. This is particularly applicable for the automotive and aerospace industries. Consider a lightweight part on an airplane over a service life of 20 years. The result can be a significant savings in fuel consumption and pollutant release.

Few materials are available for AM

This myth may be true in some instances. Materials for any manufacturing process, including AM, must be available in the proper form and perform acceptably in service. Due to the varied feedstock types, and binding and deposition methods, materials for AM vary widely.

Some processes, such as polymer MJT and VPP, rely on specialized materials, typically photopolymers. Others, such as BJT and sheet lamination (SHL), can work with many common base materials, but often require custom binding agents. Much of design and engineering is related to material choice based on historical use. Engineers typically select a part's material based on past designs made using conventional production methods. Being restricted to alternate and unfamiliar materials qualified for AM presents a barrier for many designers. An alternative is to consider the function of a material when coupled with good design for AM, although this may require additional time and testing.

Materials, such as aluminum alloy Scalmalloy from APWorks, are being developed specifically for metal AM. In the future, more specialized materials will become available for AM. Materials producers understand that developing a new material for AM or any manufacturing process can be expensive. The investment may not be justified if the potential sales volume is small.

Metal AM produces parts inexpensively

A surprising number of people believe AM can produce parts at a lower cost than conventional manufacturing. In some cases, this may be true, but AM is generally more expensive, especially as part size and production volume increase. AM is usually cost-effective when it adds value to a product beyond what is possible with conventional manufacturing.

The following illustration shows how conventional manufacturing part cost decreases as quantity increases. With AM, costs remain roughly constant, with some exceptions. The break-even point—where the two lines cross—varies widely. It depends on the size of the part, price of the feedstock, and speed of the machine, coupled with other factors such as machine depreciation.

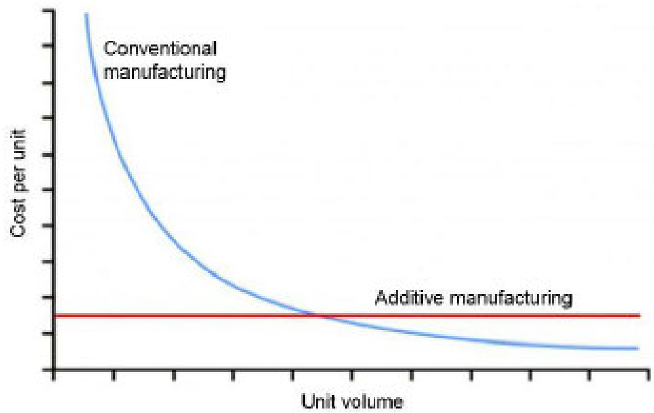


Fig. 80. Conventional manufacturing part costs typically decrease as quantities increase, but with AM, costs remain mostly constant; source: Wohlers Associates

AM parts are inferior to conventional parts

Articles and research studies often highlight differences between the properties of polymer and metal AM parts and those produced by conventional manufacturing. This should not be viewed negatively for AM. Polymer AM parts can be made with properties that are acceptable or may even exceed those obtained by conventional manufacturing. The properties may be different, but it does not mean they are inferior. With the right post-processing and heat treatment, metal AM parts can match forged or wrought materials and exceed the properties of cast parts. Nearly any material with known, reliable properties may be used if the part is properly designed to take those properties into account.

For AM to add value, it is important to design for AM. If the design reduces part numbers, material, and weight, and improves product performance, the outcome may be more favorable than suggested by the material properties. In fact, a cost reduction in material and weight can offer the option of using a stronger and more expensive material. This can result in improved functionality. The total material cost of production may be lower because less material is used, and it is lighter in weight.

Every home will have a 3D printer

Some believe 3D printers will eventually be found in most homes to produce all types of products. This is highly unlikely in the foreseeable future. Most modern products integrate a range of plastics, metals, and electronics. High-end systems may be capable of processing a combination of materials in the future. However, they will be expensive and require special training and expertise to operate. Even the most basic desktop 3D printers require design skills, software tools, and continuous maintenance beyond what most consumers would expect or accept.

Simple and low-cost 3D printers aimed at children and hobbyists may eventually become a household commodity. However, they will be suited for a limited number of materials, sizes, and types of parts. Safety, part availability and licensing, and liability are also considerations. A 3D printer designed for custom food, such as chocolates, is another possibility for homes.

The idea of 3D printing at home is akin to sewing machines. When they became affordable and easy to use decades ago, some people bought them. Today, however, few people make and wear homemade clothing, even though most of us could.

PART 2: MATERIALS AND PROCESSES

Additive manufacturing (AM) is the process of joining materials, usually layer-by-layer, to create a part. AM encompasses many materials and processes to serve various industries and applications. The AM ecosystem continues to expand, with new systems and materials being released regularly.

This part of the *Wohlers Report* details the seven AM processes and available materials, including a section on third-party material producers. AM machines and materials are only one part of the value chain. Many other important processes, technologies, and businesses support the AM industry. Parts 1, 4, and 7 of this report detail many activities surrounding AM for series production and other applications.

Processes

In general, AM processes have a lot in common with one another. For example, 3D model data serves as input to all systems. Also, fabrication occurs by joining materials in successive layers.

The following are the seven industry standard AM process categories as defined in ISO/ASTM 52900 Standard Terminology for Additive Manufacturing.

- Material extrusion (MEX)—an additive manufacturing process in which material is selectively dispensed through a nozzle or orifice
- Vat photopolymerization (VPP)—an additive manufacturing process in which liquid photopolymer in a vat is selectively cured by light-activated polymerization
- Powder bed fusion (PBF)—an additive manufacturing process in which thermal energy selectively fuses regions of a powder bed
- Binder jetting (BJT)—an additive manufacturing process in which a liquid bonding agent is selectively deposited to join powder materials
- Material jetting (MJT)—an additive manufacturing process in which droplets of feedstock material are selectively deposited
- Directed energy deposition (DED)—an additive manufacturing process in which focused thermal energy is used to fuse materials by melting as they are being deposited
- Sheet lamination (SHL)—an additive manufacturing process in which sheets of material are bonded to form a part

The differences between AM process categories can be confusing. The distinguishing features of the classifications are the nature of the feedstock and the binding mechanism. System manufacturers have created unique process names to differentiate themselves from competitors. This compounds the confusion because many of the “different” systems employ similar materials and processes.

Nearly all commercially available AM systems fit into one of the seven categories. One exception is cold spray. Future processes could emerge that do not fit into one of the categories. The ISO/ASTM 52900 standard can be updated to support changes in the future. This is the responsibility of the ISO/ASTM Joint Group 51 on terminology for AM.

The following sections provide detailed information on the seven AM processes, along with brief descriptions of machines that fall into these categories. The "system manufacturers" part of this report provides detailed information on commercially available AM systems from around the world.

Material extrusion

MEX is an AM process in which material is dispensed through a nozzle or orifice. The process was pioneered by Stratasys and introduced commercially by the company in 1991. MEX machines force semi-liquid material through a nozzle attached to an extrusion head as it or the build platform moves. For most MEX systems, the extrusion head or build platform moves in the horizontal, *x-y* plane. Once a layer is complete, the build platform moves down or the extrusion head moves up the thickness of one layer (the *z* plane). The next layer is extruded, bonding to the previous layer.

The most common feedstock for MEX is an amorphous thermoplastic polymer filament (i.e., wire-like of uniform cross section) coiled onto a spool. The filament is heated and extruded. Common feedstock includes polylactic acid (PLA) and acrylonitrile butadiene styrene (ABS).

Feedstock is not limited to thermoplastics. Viscous liquids, gels, and slurries can be dispensed, often without heating. Materials include ceramics, composites, metal-filled clays, concrete, chocolate and other foods, and living cells suspended in a hydrogel. Thermoplastic pellets are also used, which can be about 10 times less expensive than filaments. Manufacturers, such as Titan Robotics, offer pellet-fed MEX systems.

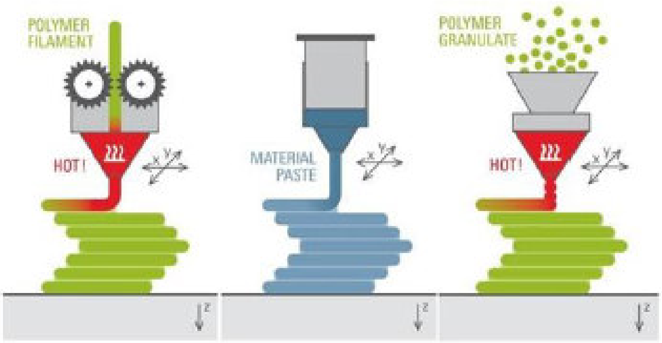


Fig. 81. Schematic of filament (left), paste (center), and pellets (right) MEX, courtesy of Steffen Ritter

MEX systems are often relatively inexpensive and easy to operate, compared to other AM processes. The process does require support structures for overhanging features. Most systems are equipped with only one extrusion head, which typically extrudes one material per layer.

Machines with two or more extruders are also available. Additional extruders usually deposit a sacrificial support material, which is manually broken away or dissolved after printing. If the support structures and part are the same material, the supports must be removed manually.

This typically produces a rough surface where the supports contact the part. It may be difficult or impossible to remove supports from internal features such as holes and channels. Soluble support material makes it possible to include more complex and delicate features in a design.

Historically, MEX parts are anisotropic, meaning their properties vary depending on the test direction. The most common anisotropy is due to differences in the structure of the material extruded on the "road path" and the interface between road paths. Porosity arising from incomplete feedstock filling a space is another cause for anisotropy. Typically, MEX parts have similar properties in the *x-y* direction, but different properties in the *z* direction. Bond3D claims it can produce isotropic part properties in polyether ether ketone (PEEK) without porosity using a proprietary pressure-controlled MEX process. The company reports that tensile bars printed in the *x*, *y*, and *z* directions have the same tensile strength.

Metals are a relatively new material for MEX. BCN3D, Desktop Metal, and Markforged offer systems in which the thermoplastic filament is impregnated with small metal particles. Parts must be debound after printing is complete, followed by sintering to bond the metal particles. This results in an almost fully dense part. The processing of metal by MEX is relatively slow compared to other metal AM processes.

MEX systems represent the largest installation base of low-cost desktop 3D printers, many of which are derived from the RepRap open-source project. A few of the companies that offer these machines and industrial systems include BCN3D, FAME 3D (Lulzbot), Raise3D, and Ultimaker.

BotFactory produces machines for building printed circuit boards (PCBs) using conductive inks. Novameat, Redefine Meat, and Steakholder Foods are using MEX to print animal- and plant-based meats. Other companies are using the process to print candies, chocolates, and biomaterials.

Companies are creating large MEX systems to print furniture, tooling, and building materials. Concrete feedstock is used for the construction of large objects, such as bridges, parts of buildings, and outdoor accessories. Among the companies that offer these systems are 3D Platform, COBOD, CyBe Construction, ICON, Mighty Buildings, Thermwood, WASP, and Winsun.

Fig. 82. Concrete MEX bench and planters, courtesy of COBOD

Vat photopolymerization

VPP is a process in which liquid photopolymer is placed in a container and selectively cured by light-activated polymerization. VPP was the first patented and commercialized AM process, initially called stereolithography. The first systems used an ultraviolet (UV) laser and x-y scanning mirrors on computer-controlled galvanometers. The system scanned a low-power UV light beam over the top surface of the liquid thermoset photopolymer, polymerizing (curing) and adhering the layer to the previous one.

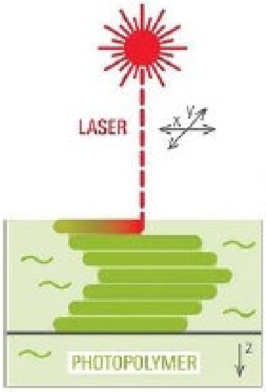


Fig. 83. Schematic of VPP, courtesy of Steffen Ritter

VPP systems are desirable for high-resolution parts at a reasonable cost. Layers of 10 µm (0.0004 in) are achievable and produce a finer resolution than most other AM processes. VPP requires support structures, which are typically removed manually. Scan strategies have been developed to minimize laser scanning time to increase productivity. One result is a volume of uncured polymer trapped inside. Parts are fully cured using UV light.

Many VPP machines use a lamp or light-emitting diodes (LEDs) as the energy source, coupled with digital light processing (DLP) technology. A DLP unit is comprised of a micromirror array, and each micromirror is independently activated. The activated micromirror projects light onto the top or bottom surface of a vat. A set of activated spots make up the desired image. This technique cures an entire layer at once, making it potentially faster than scanning a single point of laser light across a surface.

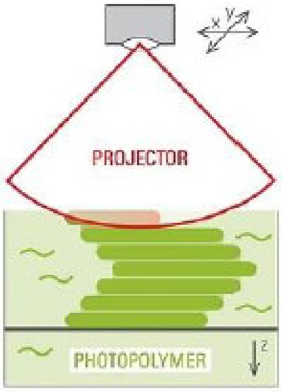


Fig. 84. Schematic of DLP-based VPP, courtesy of Steffen Ritter

Advances in DLP technology have resulted in high-resolution and fine-featured parts. However, DLP does not scale well to large areas due to technical challenges and high costs. Typically, DLP systems project light from below the vat and cure photosensitive resin through a transparent floor, known as an optical window. This method requires only a relatively small amount of liquid in the vat compared to machines that cure the top surface of the resin.

With bottom-curing systems, the optical window is covered by a thin film or a polymer coating. This is necessary to prevent the cured layer from adhering to the optical window. For windows using a film, each layer is cured between the film and the previous layer of the part. The new layer is mechanically separated from the film. Windows with a coating create oxygen-filled barriers between the glass and the polymer. The oxygen inhibits polymerization, creating a liquid film between the optical window and curing surface. For certain types of parts, this can speed the build process.

Fig. 85. Part being produced from bottom-curing DLP-based VPP system, courtesy of Carbon

Among the companies that offer industrial DLP VPP systems are 3DCeram Sinto, Carbon, Coobx, DWS, Lithoz, Novafab, Prodways, and Rapid Shape. The proprietary MovingLight technology from Prodways employs LEDs and DLP technology in a curing unit that moves above the vat of resin on a gantry system. Axtra3D's patented Hybrid PhotoSynthesis Technology employs DLP to cure most of a layer and a UV laser to polymerize the perimeters.

Many low-cost desktop VPP systems have been introduced since Formlabs commercialized the Form 1 in 2013. They include the Photon Mono series from Anycubic, Form3+ from Formlabs, SL1S from Prusa, and Proxima 6.0 from Voxelab.

Fig. 86. Figurines printed on the Prusa SL1 with support structures still attached, courtesy of Prusa

Other variations of the VPP process have been commercialized. Some systems from ETEC (formerly Envisiontec) employ lasers and a proprietary scanning technology called 3SP (for scan, spin, and selectively photocure). 3SP employs a rapidly spinning mirror that reflects the laser beam through a series of optical elements onto the top surface of the vat.

Another variation is thin-film photopolymerization. A thin layer of photopolymer is pulled across the exposure area, contacting the surface of the previous layer. A full layer is then imaged through the film. The technology is used in the ProJet and ProX series VPP systems from 3D Systems. The Korean company Carima uses a similar technology with its DM 400 system.

The VPP process can produce ceramic and metal parts. Microparticle powder is added to photopolymer and becomes suspended in the liquid resin. The parts must go through debinding and sintering to produce a near-full-density ceramic or metal part. The index of refraction of the particles and resin must be matched to prevent multiple reflections of the laser at resin-particle interfaces.

Fig. 87. Ceramic lattice structure (light gray) for an antenna measuring 68 x 70 x 12 mm (2.7 x 2.8 x 0.5 in), courtesy of 3DCeram Sinto and Anywaves

Multi-photon lithography systems produce parts with micron resolution. These parts are being used increasingly for microelectronic and microfluidic applications. Overall part dimensions are typically less than 1 mm (0.039 in). The following image shows a part in which the photopolymer is infiltrated with silica nanoparticles. The part requires debinding and sintering.

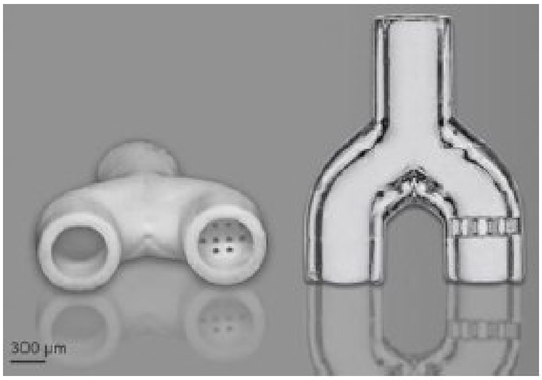


Fig. 88. "Green" microfluidics Y-connector (left) and fully cured glass structure (right) produced by two-photon VPP, courtesy of Nanoscribe and Glassomer

Powder bed fusion

PBF is a process in which thermal energy selectively fuses regions of a powder bed surface. Thermal energy from a laser, electron beam, or another source melts either a portion or all the powder in a layer. The area adheres to the previous layer and becomes solid as the material cools. Once the layer has been fused, a new layer of powder is added.

The layer thickness is dependent on the powder size, material, and machine specifications. Typical layer thickness is 100 µm (0.004 in) for polymer feedstock and 50 µm (0.002 in) for metal powder, but the thickness can vary from one build to the next.

The term laser sintering is used in the AM industry to refer to laser polymer PBF processes. Terms for metal processing include selective laser melting, direct metal laser sintering, and electron beam melting, but they are not standard across the industry and sometimes misunderstood.

A wide range of polymers and metals are suitable for PBF. Typically, polymers are semi-crystalline thermoplastics, including PA11, PA12, and PEEK. This polymer class exhibits an unusual melting and crystallization behavior. It results in part forming with virtually no residual stress when the powder bed is heated.

Fig. 89. Loose powder from a PBF system, courtesy of the University of Manchester School of Architecture

Unfused, loose powder surrounding a part serves as a support system. The unfused polymer powder slowly degrades each time it is exposed to elevated temperature in the build chamber.

For this reason, some feedstock, such as PA12, can only be reused if mixed with 20–50% virgin (new) material.

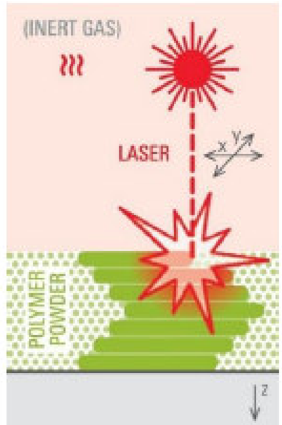


Fig. 90. Schematic of polymer PBF, courtesy of Steffen Ritter

For metal PBF, commercial feedstocks are typically metals that can be easily fusion-welded or cast. Support structures are required to anchor parts and features to the build plate. Thermal gradients in the build chamber are high, which leads to significant thermal stresses. The thick build plate serves as a heat sink and prevents parts from distorting and warping during the build.

PBF systems are relatively complex and expensive compared to most other AM processes, especially for metals. Operating costs are comparatively high due to facility requirements for inert gas and safe powder handling. High feedstock cost and polymer recycling issues also increase operating costs. Efforts are underway by many companies to reduce the time and cost of material handling and post-processing.

Parts made using PBF are increasingly being used for final manufacturing applications. This is because the process creates favorable part quality and desirable mechanical properties. Also, a relatively large range of metal powders is available. Equipment manufacturers are incrementally including process control capabilities in their machines to ensure repeatable results. These matters are discussed at length in Part 4 of this report.

The energy source for most metal PBF processes is a laser or an electron beam. Laser-based metal PBF systems generally produce a better surface finish and finer features compared to electron beam systems. Electron beam systems are typically more expensive but build parts faster than laser systems.

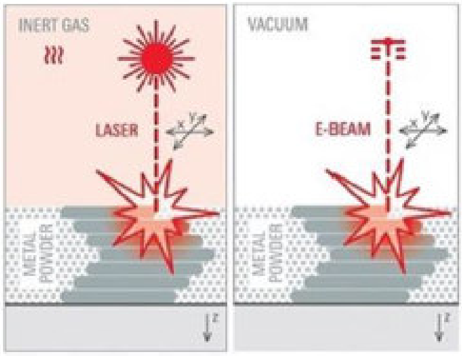


Fig. 91. Schematics of laser (left) and electron beam (right) PBF, courtesy of Steffen Ritter

Electron beam systems produce less residual stress, resulting in less distortion and a reduced need for anchors and support structures. Some loose powder near the electron beam path is partially sintered, making it sometimes difficult to clear unused powder from holes, interior channels, and passageways. This is especially true when the features are small and deep within a part. This makes electron beam systems less desirable for parts with fine channels built into them.

High speed sintering (HSS) is a PBF process originally developed at Loughborough University and commercialized by Voxeljet. Print heads selectively deposit a black infrared-absorbing ink onto a powder bed. Infrared lamps irradiate the entire surface of the bed. The areas with the ink absorb sufficient energy to melt the underlying powder. multi jet fusion (MJF) technology from HP operates on the same principle and jets a second "detailing" agent to improve the definition of edges. In 2021, Stratasys released the H350, which uses Selective Absorption Fusion (SAF) technology, a branded version of HSS.

Fig. 92. Schematic of HSS process, courtesy of Steffen Ritter

Many companies offer PBF systems. 3D Systems has sold machines using selective laser sintering technology for many years. The company acquired Phenix Systems in 2013 and LayerWise in 2014. 3D Systems' metal PBF machines are derived from both companies. EOS also pioneered systems for polymers and metals. The company calls its metal process direct metal laser sintering. Each EOS machine model is dedicated to a specific class of material. The "P" and "M" models process polymer and metal powders, respectively.

Renishaw refers to its process as laser melting, while GE Additive's Concept Laser is called LaserCUSING. Some system manufacturers and users refer to the technology as selective laser melting (SLM). This can be confusing because of the company named SLM Solutions, which refers to its metal PBF as SLM. The Arcam system from GE Additive calls its PBF process electron beam melting. The Japanese companies Matsuura and Sodick offer hybrid systems that combine metal PBF with computer numerical control (CNC) milling.

Fig. 93. Gas combustor part produced by hybrid PBF and CNC milling, courtesy of Matsuura

Many other companies around the world sell PBF systems. They include Aspect of Japan, Intech Additive Solutions of India, Sinterit of Poland, Sintratec of Switzerland, and XYZprinting of Taiwan. Chinese companies offering PBF systems include Bright Laser Technologies, Farsoon, Huake 3D, and TPM3D.

Material jetting

MJT uses inkjet print heads to deposit droplets of build material. The droplets are dispensed selectively as one or more print heads move across the build area. Feedstocks are typically photopolymers or wax-like substances to build parts that can be used as investment casting patterns. Metal MJT, however, is also beginning to develop. Among the companies that manufacture MJT systems are 3D Systems, Mimaki, Nano Dimension, Solidscape (a Prodways company), Stratasys, and XJet.

MJT systems often use multi-nozzle print heads to increase build speed and print different materials. This facilitates the printing of sacrificial support material, a second build material, or even graded material combinations. The J-series PolyJet system from Stratasys produces parts by simultaneously jetting three different build materials. Parts, or regions of parts, are built in a range of colors and material properties. This is accomplished by controlling the proportions of the three materials. The materials are photopolymers that cure with UV light exposure as they are deposited.

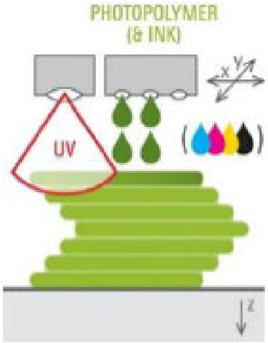


Fig. 94. Schematic of the MJT process, courtesy of Steffen Ritter

3D Systems offers an MJT process called multijet printing that produces graded materials. The Dragonfly system from Nano Dimension jets build material and conductive inks to produce functional PCBs. The SV2 printer from BotFactory uses a similar inkjet process.

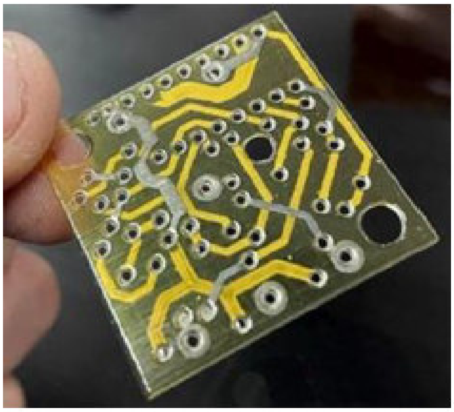


Fig. 95. 3D-printed circuit board, courtesy of BotFactory

Machines from Solidscape produce wax parts, which are usually used as patterns for the investment casting of metal parts, such as jewelry. The process uses a proprietary inkjet process combined with horizontal milling of each layer. Unlike most MJT systems, Solidscape uses a thermoplastic, so it does not require UV curing after it is jetted.

Fig. 96. Wax pattern for jewelry casting, courtesy of Solidscape

Arburg introduced a process in 2013 that closely resembles MJT. The company's Freeformer system deposits droplets of melted thermoplastic at a frequency of 60–200 hertz. Freeformer feedstock is standard thermoplastic pellets, which are less expensive than filament.

A different type of material deposition, often referred to as "direct-write" technology, deposits functional "inks." These systems atomize nanoparticle materials while merging with an inert carrier gas into an aerosol. The aerosol is propelled onto a surface. An annular stream of jetted gas focuses the aerosol jet into a thin line. The print materials can be a metal or non-metal, as well as conductors or dielectrics, supporting the printing of electronic circuits.

Direct-write material deposition is generally incapable of creating 3D shapes because it operates in 2.5 dimensions, similar to a 2.5-axis CNC milling machine. The deposition rate is typically very low. However, when equipped with a proper motion system, direct-write systems can deposit material on curved surfaces and even around corners. Two companies that offer direct-write systems are nScrypt and Optomec.

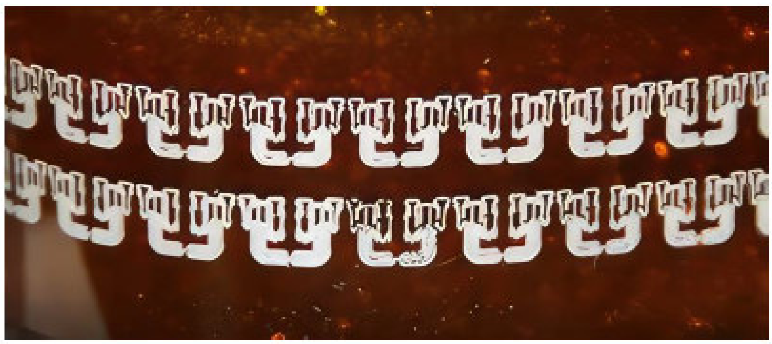


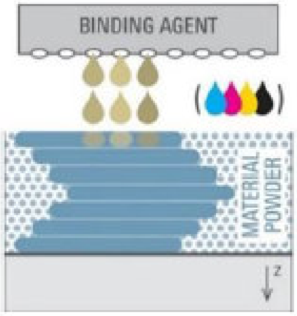
Fig. 97. Resistors printed on a curved surface, courtesy of nScrypt

Binder jetting

BJT is a process in which a liquid bonding agent is selectively deposited to join fine particles in a powder bed. The process is similar to MJT in its use of inkjet print heads. The difference is that with BJT, the dispensed material is not the main build material, but rather a liquid that binds particles and layers of powder into the desired shape.

The BJT process was originally developed at Massachusetts Institute of Technology (MIT) and was called 3D printing. The first commercial spinoff company, Soligen, was founded in 1991. Early licensees of MIT's technology included ExOne (originally Extrude Hone), Soligen, Specific Surface, Therics, and Z Corp. (acquired by 3D Systems in 2012). After the expiration of the original BJT patents, companies such as Desktop Metal, Digital Metal, GE Additive, and HP announced BJT systems for producing metal parts. In all cases, post-processing is necessary to remove the binder and form a strong, dense metal part.

Fig. 98. Schematic of BJT process, courtesy of Steffen Ritter



Color BJT, developed and first commercialized by Z Corp., is offered by 3D Systems as part of the company's ProJet CJP series. It uses pulverized plaster powders and a water-based binder. Taiwan's Microjet Technology also offers machines based on BJT.

Fig. 99. Full-color BJT model built using a ProJet printer, courtesy of 3D Systems

Systems from ExOne jet a liquid binder onto the surface of metal powder or sand. Metal parts produced by BJT require debinding and sintering in a furnace to produce usable parts. Sintered metal parts shrink, often in the range of 20%. Due to this significant shrinking, it can be difficult to accurately build large parts and some complex features. To reduce distortion and produce a fully dense part, the porous metal can be infiltrated with a second, lower-melting-point metal. A popular example is stainless steel infiltrated with bronze.

ExOne offers large build volumes for both sand and metal. These machines are capable of building parts at relatively high speeds, although for metal parts, it is important to consider the additional time for post-processing.

ExOne's Innovent+ system uses an ultrasonic recoater to support printing with standard metal injection molding (MIM) powders. These materials are commonly available and are less expensive than gas-atomized metal powder.

Fig. 100. Part produced using BJT and MIM powder, courtesy of ExOne

Digital Metal is a Swedish company previously owned by Höganäs and acquired by Markforged in 2022. It has developed a BJT system for metals and ceramics with a focus on stainless steel. The company began selling systems in 2016 after many years of making parts as a service provider.

Voxeljet offers large systems with wide print heads. The powder materials used by Voxeljet include polymethyl methacrylate (PMMA) and foundry sand. The binder reacts at room temperature but must cure in the powder bed for a few hours before the parts can be removed.

Fig. 101. Sand printer with build volume of 4 x 2 x 1 m (13.1 x 6.6 x 3.3 ft), courtesy of Tooling & Equipment International

3DEO has developed a proprietary BJT process that uses MIM powder. A binding agent is deposited across the entire build area. Up to eight CNC end mills cut the topology. The milling process can be one layer at a time or up to 10 layers to improve surface finish. The following image shows a bolt release for a rifle measuring 19 x 4 x 12 mm (0.75 x 0.16 x 0.47 in). The part cost was reduced by 25%, with an annual savings of $118,000, according to 3DEO.

Fig. 102. Bolt release, courtesy of 3DEO

Directed energy deposition

The DED process uses focused thermal energy to fuse materials by melting as they are being deposited. A laser or electron beam usually serves as the energy source, and the material is a metal powder or wire. The process produces near-net-shape parts, usually requiring machining to achieve required tolerances.

The DED process offers unique capabilities. For example, more than one material can be deposited simultaneously, making functionally graded parts possible. Also, most DED systems use a 4- or 5-axis motion system to position the deposition head. The process is not limited to horizontal layers. For example, it is possible to produce curved layers with DED. This capability makes the process suitable for adding material to an existing part, such as repairing worn areas or adding features to a part or tool. The DED process is well suited for producing large metal parts.

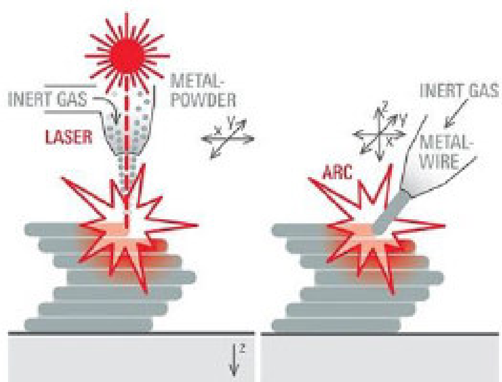


Fig. 103. Schematic of powder-fed (left) and wire-fed (right) DED system, courtesy of Steffen Ritter

Laser engineered net shaping (LENS) from Optomec injects a metal powder into a pool of molten metal created by a focused laser beam. BeAM, acquired by AddUp in 2018, sells its Modulo and Magic series DED machines. Trumpf, a large manufacturer of industrial equipment and laser systems, offers its TruLaser DED systems and upgrade options to convert existing laser welding systems into metal AM machines.

Fig. 104. LENS process, courtesy of Optomec

Sciaky offers a DED process in which an electron beam is the energy source and the feedstock is in wire form. A Ukrainian company named xBeam has developed a DED process that uses electron beam energy and metal wire as feedstock. The xBeam process involves a unique hollow cone beam in a vacuum for melting material, including reactive and refractory metals.

In 2021, xBeam showed copper parts made on the system. Historically, it has been challenging to create copper DED parts due to problems controlling the oxygen level within a system. Prior to getting into the AM industry, xBeam manufactured and sold electron beam guns under the company and brand Chervona Hvilya.

Fig. 105. Copper parts made using xBeam process, courtesy of xBeam

Digital Alloys has developed Joule, a wire-based DED system. The print head runs electrical current through the feedstock to melt it to previous layers. The process resembles wire-feed welding but creates no arc. Norsk Titanium has developed rapid plasma deposition, a variation of DED, using a plasma arc to melt titanium alloy wire.

Fig. 106. Damaged gear housing (left), after DED (center), and after machining (right), courtesy of Optomec

Most hybrid AM systems combine DED with CNC milling. Machining helps produce surfaces and features at tight tolerances. Many companies have introduced systems since 2013, including DMG Mori, DMS, and Hermle.

Fig. 107. DED process (left) and machined part (right), courtesy of DMG Mori

Hybrid Manufacturing Technologies introduced its deposition head with the first commercially available hybrid DED/CNC machine in 2013. The patented Ambit tool-changeable metal powder deposition head was integrated into a Hamuel HSTM1000 CNC machine. Since then, the company has co-developed many new hybrid CNC machines with several machine tool manufacturers, including ELB and Mazak.

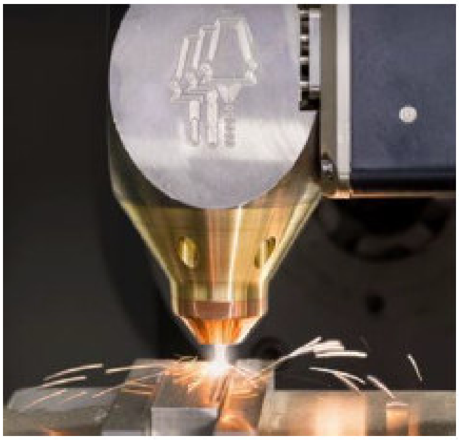


Fig. 108. Ambit attachment for CNC machine, courtesy of Hybrid Manufacturing Technologies

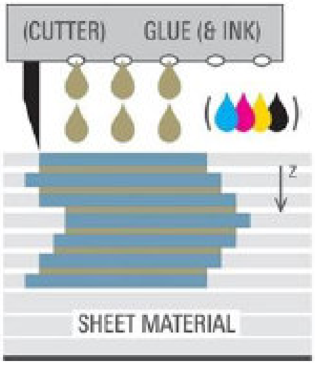
The Ambit technology is installed on a relatively high percentage of commercially available metal hybrid CNC systems. Ambit heads can be installed as retrofits on most vertical CNC machines.

Sheet lamination

SHL is a process in which sheets of material are bonded to form a part. Materials can be adhesive-coated papers that form a part when laminated. Metal tapes and foils are used to create metal parts. Layer contours are typically generated by a machining process either before or after a layer of material is deposited.

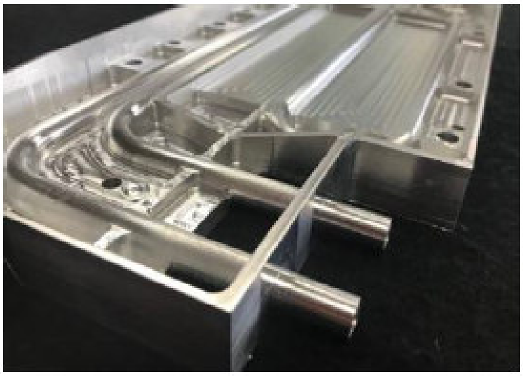
The first commercialized SHL technology was laminated object manufacturing from Helisys in 1992, based on a patent filed six years earlier. The feedstock is a roll of kraft paper commonly used by butchers for wrapping meat. One side of the paper is coated with a polymer, which serves as an adhesive. A heated roller joins successive layers, and a laser beam cuts a 2D profile of the part at each layer.

Fig. 109. Schematic of SHL process, courtesy of Steffen Ritter



Ultrasonic additive manufacturing (UAM) from Fabrisonic is another SHL technology. UAM uses ultrasonic welding to bond layers of thin metal tapes and foils. Layers are welded using ultrasonic vibration supplied by two high-frequency transducers, coupled with force created by a rolling sonotrode called a horn. Intermittent machining of layers produces the part contours. Fabrisonic offers systems that combine UAM with full CNC-machining capabilities. The process can embed electronics and other low-melting-point materials in a part.

Fig. 110. Heat exchanger made by UAM, courtesy of NASA's Jet Propulsion Laboratory and Fabrisonic



Impossible Objects has developed a type of SHL that uses composite materials. The process jets adhesive onto carbon-fiber or fiberglass sheets and dispenses polymer powder on each sheet. The sheets are bonded one at a time. The build is then heated in an oven to melt the polymer. Excess material is dissolved or trimmed away to reveal one or more solid composite parts.

Fig. 111. Composite bicycle pedals made using SHL, courtesy of Impossible Objects

Materials

Polymers and metals are the two major categories of AM materials. A variety of filled and composite materials are also available, as well as ceramics and cermets (ceramic-metal hybrids). It is helpful to group materials into functional categories and types. Examples include materials used as patterns for investment- and sand-casting applications.

Polymers

Many polymer options are available for AM, but offerings are small compared to those for conventional manufacturing. AM materials may be selected based on tensile strength, rigidity, biocompatibility, glass transition temperature, color, and transparency. Additional properties include moisture resistance, sterilizability, fire retardancy, and smoke and toxic emissions. Materials range from hard and stiff to soft, rubber-like elastomers.

Polymers are classified into two groups based on their behavior at high temperatures. Thermoplastics can be repeatedly melted, cooled, and solidified. They retain their properties, although some degradation can occur, particularly with repeated high-temperature exposure. Thermoset polymers are permanently cured once they are polymerized. After polymerization, thermosets do not melt. Photopolymers, like those used in VPP and MJT, are liquid thermoset resins that are polymerized when exposed to certain wavelengths of light.

Materials used in MEX systems are almost exclusively thermoplastics, such as ABS, polycarbonate (PC), PC/ABS blends, polyamides (PA), and PLA. 3DXTech, Stratasys, and others offer ULTEM 9085 and ULTEM 1010. These thermoplastic polyetherimides have a high strength-to-weight ratio and good fire, smoke, and toxicity properties, making them well suited for aerospace applications.

Fig. 112. Fume collecting nozzle made in ULTEM 1010 for an aerospace assembly, courtesy of Collins Aerospace

The materials available for low-cost MEX 3D printers were limited to ABS and PLA until 2012 when Taulman3D introduced a nylon copolymer filament. Since then, filament offerings have increased considerably. Users can purchase high-impact polystyrene (HIPS), PC, polyethylene terephthalate (PET), and polyvinyl alcohol (PVA). Soft, rubber-like materials are also available, including soft PLA, thermoplastic polyurethane (TPU), and thermoplastic elastomer (TPE).

A few companies have developed 3D printers that extrude silicone rubber. The two-part thermoset is extruded as a liquid and cures before the next layer is deposited.

Fig. 113. Waterproof silicone wire connectors, courtesy of Spectroplast

Filament producers ColorFabb, Proto-pasta, TreeD, and others make "exotic" MEX feedstock by adding functional or aesthetic fillers to a polymer base. They include bamboo-, clay-, and copper-filled materials. Some metal-filled filaments can be used to create metal parts. They are printed on an MEX system, debound, and sintered in a furnace to yield a fully dense metal part, although with significant shrink. BCN3D, Desktop Metal, and Markforged have integrated this capability into proprietary systems, while BASF's Ultrafuse filaments can be used with nearly any MEX system.

Fig. 114. 316L stainless steel parts from Ultrafuse filament, courtesy of BASF

PA is the most common polymer for PBF and is available in PA12, PA11, PA6, and other grades. Nylon is a synthetic PA and the two terms are often used interchangeably. Other polymers for PBF include polystyrene and polypropylene (PP), as well as glass-, carbon, mineral-, and aluminum-filled PA powders. EOS offers polyaryletherketone (PAEK), which is said to offer favorable strength, wear resistance, high-temperature stability, fire, smoke, and toxicity properties.

Fig. 115. Aluminum-filled PA12 smart phone stand, courtesy of EOS

Many companies, including Materialise, produce TPU parts using PBF. These parts exhibit high toughness, tear resistance, and elasticity. 3D Systems offers DuraForm Flex, an elastomeric PA powder. BASF and Lubrizol offer TPU powders for multi jet fusion systems from HP. Lubrizol also offers TPU for MEX systems.

Fig. 116. Flexible axle boot made in TPU, courtesy of Makenica

The materials used in MJT and VPP processes are mainly photopolymers. Mimaki and Stratasys support full-color AM with both soft and rigid materials.

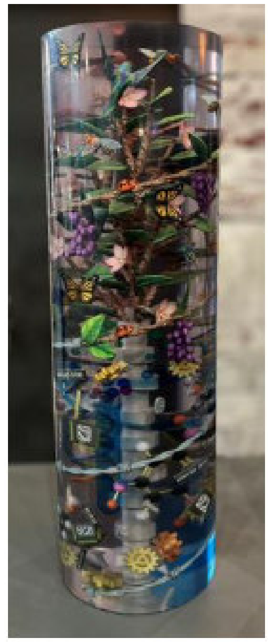


Fig. 117. Full-color, transparent part produced on an MJT system from Mimaki, courtesy of Olaf Diegel

New polymer products

by David Espalin

In 2022, researchers developed new polymer materials for a range of AM processes. They reflect increased interest in more sustainable parts with greater chemical resistance and advanced mechanical properties.

BASF released Ultrasint AP26, a more sustainable polybutylene terephthalate (PBT) for PBF systems. BASF claims this material is the first PBT for AM to support up to 100% reusability, potentially resulting in no waste.

Fig. 118. PBF part made with Ultrasint AP26 material, courtesy of BASF

Rogers Corp. recently released a material called Radix for use in VPP systems. This ceramic-filled, UV-curable polymer is suitable for printing radio frequency dielectric components with low loss at 24 GHz and low moisture absorption. These characteristics play critical roles in the performance of antennas, test and measurement devices, and communication systems.

Fig. 119. Latticed sphere made from Radix material, courtesy of Rogers Corp.

Carbon released three new elastomeric polyurethane (EPU) materials for use in its AM process. EPU 43, EPU 44, and EPU 45 have elongation-to-break values of 250–300% and are designed to compete with thermoplastic polyurethanes. These new material variants are suited to specialized applications that require shock absorption, energy damping, durability, and resiliency. The materials have improved strength in the green state, making complex lattice structures possible. EPU 44 is a 40% bio-based material designed to be highly sustainable, while retaining performance metrics expected from EPUs.

Fig. 120. Complex latticed midsole 3D-printed in EPU 45, courtesy of Carbon

Airtech has added Dahltram U-350CF to its range of registered materials for use in large-scale MEX. This modified polyethersulfone carbon-fiber-filled composite can be used in temperatures of up to 204°C (400°F). Airtech claims the material provides high strength at high temperatures, greater stiffness for high-temperature tooling applications, and lower creep and warping.

ColorFabb's new MEX filament allPHA is a bioplastic polyhydroxyalkanoate that is said to promote sustainability. This natural polyester is produced by fermenting bacteria in the presence of natural sugars and oils. The material is 100% bio-based and biodegradable and is suitable for projects that have environmental disposability as one of the priorities.

Chromatic 3D Materials has introduced new MEX thermoset polymers. ChromaLast 65 is suitable for static and dynamic loads, while ChromaFlow 70 is available in high-flow textile grades. These polyurethanes exhibit isotropic tensile properties and are capable of sealing tightly against gases and liquids. Notable chemical properties include flame retardancy, resistance to compressor- and mineral oils, and strong adhesion to metals and fabrics. Also, ChromaFlow 70 can be used in large-scale printing without warping. Some common applications for these materials include seals and gaskets, bellows, and belts for material handling.

In 2022, a trend emerged to blend PC with other polymers to achieve higher chemical resistance in MEX materials. For large-scale AM, Sabic released XYLEX resins, which blend PC and an amorphous polyester. These materials offer strong chemical resistance to pool and spa chemicals, automotive fluids, alcohols, and cleaning fluids, Consequently, they resist stress cracks, according to the company.

PC-PBT from Polymaker is a blend that combines the chemical resistance of polybutylene terephthalate with the strength and toughness of PC. It is said to perform well in extreme environments, whether in contact with hydrocarbon-based chemicals (e.g., alcohols, fuels, and oils) or inorganic aqueous salts. It also maintains toughness and ductile fracture behavior at low temperatures.

Polymer pricing

AM polymers are typically more expensive than equivalent materials for conventional manufacturing. Most photopolymers, thermoplastics, and composites for industrial AM systems fall within the range of $40–250 per kg ($18–114 per lb). By contrast, thermoplastics for injection molding are typically $2–10 per kg ($0.91–4.55 per lb). This means AM polymers are 4–100 times more expensive than polymers for injection molding. Some filaments for low-cost desktop MEX printers are commonly available for $20 per kg ($9.10 per lb).

The following table provides estimated price ranges for 1 kg (2.2 lbs) of various AM polymers. The purchase quantity, product quality, and material producer contribute to setting the final price. MJF systems from HP require additional consumables, including fusing and detailing agents, cleaning rolls, and print heads, which increase operating costs. The low end of the powder price range presented in the following is for companies that operate the Jet Fusion 5220 system from HP. The cost of MJF powder doubles for companies that operate the 5200 system.

Material	Price range (per kg)
Powders	
PA12	$30–110
Glass-filled PA12	$27–100

Material	Price range (per kg)
PA11	$30–120
TPU	$50–140
Filaments	
ABS	$20–500
PLA	$20–500
ULTEM 9085	$140–890
Photopolymer	
General purpose	$50–1,000
Elastomeric	$200–800
Heat resistant	$150–800

Source: Doug Collins and Olaf Diegel

Feedstock for AM is produced in low volumes, which increases cost compared to conventional plastics. Also, polymers for AM require more processing, compared to conventional plastics processing.

Powder-based AM processes require specific particle sizes. Conventional powder is produced for a wide particle size range. The size range for AM is relatively narrow, especially for PBF. Since only some of the polymer production run is profitable, the price of the material for AM is relatively high. The need for high-quality powder and filament for AM can add significant cost to the production of the material.

Company-branded material sales are an important revenue stream for AM system manufacturers. Suppliers of materials are reluctant to give up this recurring profit by lowering prices. Consequently, prices of AM feedstock have not changed significantly in more than two decades. However, inroads are being made due to the demand for open platforms that do not require specific feedstock.

Anticipating large-scale AM adoption by major manufacturing companies, third-party material suppliers hope to capture a share of the AM materials market. Competition from these producers is expected to contribute to declining material prices. The pricing of pellet feedstock for large-format printers is relatively low, compared to most AM materials. Companies manufacturing these types of systems include Arburg and Juggerbot.

Metals

by Ryan Kircher

The range of metals and alloys available for AM continues to grow. A designer can choose from, but is not limited to, the following:

– Tool steels
– Stainless steels
– Commercially pure titanium
– Titanium alloys

- Aluminum alloys
- Nickel-based superalloys
- Cobalt-chromium alloys
- Copper alloys
- Gold
- Silver
- Platinum
- Palladium
- Tantalum
- Tungsten
- Niobium

The U.S. government's emphasis on developing hypersonic technologies supports development of high-temperature alloys for AM. For example, NASA developed copper alloy GRCop-84 for combustion chambers and other high-temperature applications. This alloy was designed specifically for AM to solve a particular technical problem.

Refractory metals are of particular interest in hypersonic applications because they maintain high structural integrity at elevated temperatures. These materials are difficult to process by traditional means (e.g., forging and casting) due to their limited toughness and high melting points. Designs are often simplified to reduce the amount of processing required. Powder-based AM processes are an attractive alternative and increase the design envelope for refractory metal parts. One of the more mature refractory alloys for AM is the Niobium-based alloy Nb C103.

BJT systems from Desktop Metal, Digital Metal, ExOne, GE Additive, and HP are used to produce metal parts. Available materials include stainless steel, Inconel, cobalt-chrome, bronze, iron, tungsten, and tungsten carbide. With some processes, the binder is burned out, and then bronze or another material is infiltrated into the parts during a post-build furnace cycle. For high-performance applications where infiltration is not an option, parts are sintered at a high temperature to produce a homogeneous metal part. Substantial shrink is typically involved in this case, however. BJT parts typically shrink in the range of 20% during the high-temperature sintering process. Adjustments are made at the design phase to account for this dimensional change.

MEX systems use filaments made from thermoplastic polymer and metal powder to produce "green" parts similar to those from BJT systems. These parts undergo a similar debinding and sintering process to remove the polymer binder and consolidate the metal powder particles. The amount of binder needed for MEX metal processing is greater than for BJT. The MEX filament must flow when melted, which limits metal particle loading.

Another key development in metal AM is the emergence of powder recycling and reclamation providers such as MolyWorks and 6K. These companies are developing methods to provide metal AM users with spherical powders derived from recycled metals. Recycled materials can come from machining chips, failed AM parts, support structures, and out-of-spec AM powder. Most metal alloy powders can be reintroduced into an AM system a limited number of times before they no longer meet specification standards.

Factors impacting the adoption of metals

A significant factor limiting the adoption of metal AM, particularly laser PBF, has been the high cost of producing parts. Recent advancements in metal PBF technology are increasing system productivity and reducing running costs.

A common approach for increasing the productivity of laser PBF is to increase the number of lasers within a system. Most major laser PBF system providers now offer multi-laser systems with expanded build capacity to make large-scale metal AM more cost-effective. One example of this approach is the NXG XII 600E from SLM Solutions, which is equipped with 12 one kilowatt lasers.

VulcanForms Inc. has invented and commercialized 100-kilowatt laser PBF technology integrated into a proprietary digital production system. The system from VulcanForms produces fully engineered metal parts by combining AM, heat treatment, surface engineering, and precision machining. The company opened two production facilities in 2022. They produce parts and assemblies for medical, defense, aerospace, and semiconductor companies.

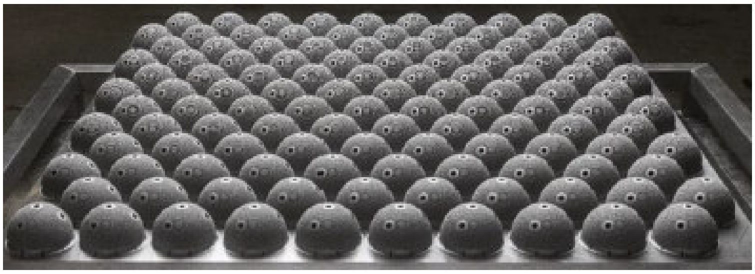


Fig. 121. 120 Ti-6AL-4V-ELI acetabular cups built simultaneously on a system from VulcanForms, courtesy of VulcanForms

Seurat Technologies has invented a laser PBF technique that uses an optically addressable light valve technology to support what the company calls area printing. The company claims the process is 10 times faster than conventional laser PBF technology.

Another development is the optimization of the laser beam thermal profile. This results in more precise control of heat deposition, which maximizes the build rate, improves material quality, and minimizes spatter and smoke. Laser PBF systems typically use single-mode lasers with a near-Gaussian beam thermal profile. This causes overheating at the center of the beam that limits how much laser power can be used, which in turn, limits build rate. One solution is to use laser beams with a variable thermal profile. An example of this is the AFX-programmable fiber laser technology from nLight. It provides a variety of optimized beam thermal profiles directly from the output fiber without using free-space optics.

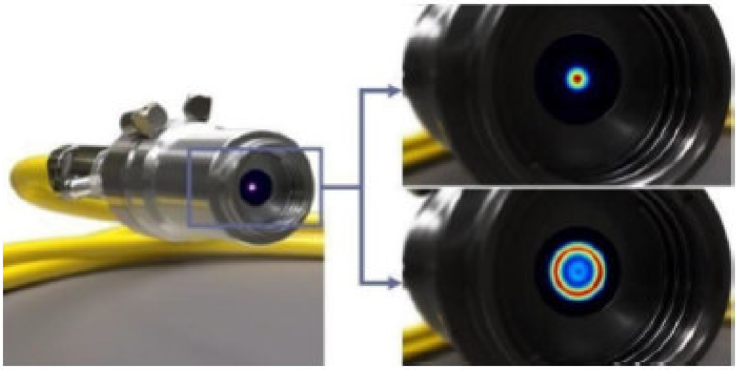


Fig. 122. AFX-programmable fiber laser technology rapidly switching the beam profile coming directly out of the fiber connector, courtesy of nLight

Another emerging metal AM process that can produce large parts at high speed is the process from MELD Manufacturing. Similar to friction stir welding, the process uses extreme pressure and friction to heat and deform a metal rod into the desired shape. Materials in the MELD process never reach a molten state. This eliminates the need for a processing chamber containing a protective atmosphere or vacuum, making it suitable for large-scale AM products.

New metal powders

New materials for PBF systems have been released by material suppliers and AM system manufacturers. Most of them are designed for end-use part production.

3D Systems has released CuNi30, a corrosion-resistant, copper-nickel alloy for use with its DMP Flex 350 metal PBF system. The alloy was developed as part of the company's collaboration with HII's Newport News Shipbuilding division. The material is aimed at replacing cast components used in a salt-water environment.

6K Additive released a new low-oxygen Ti-6Al-4V powder. The material reportedly supports an increase in production throughput, reducing overall cost.

Elementum 3D claims its patented Reactive Additive Manufacturing (RAM) technology supports the 3D printing of previously unprintable materials. The company offers a range of materials developed with the RAM technology including aluminum alloys, copper, and tantalum. A recent addition is Ni230-RAM1, a nickel-based superalloy. The company said other nickel-based superalloys are under development.

In July 2022, EOS announced four new materials for use with its M 290 laser PBF system. EOS StainlessSteel 254 is an austenitic alloy, while EOS StainlessSteel SuperDuplex is an austenitic-ferritic duplex material. EOS ToolSteel CM55 is a cobalt-free, high-strength, and high-hardness tool steel. EOS NickelAlloy HAYNES 28 is a nickel-based superalloy manufactured under license from Haynes International.

In November 2022, Canadian company Equispheres launched a less hazardous AlSi10Mg aluminum alloy powder for AM. The NExP-1 material is dust-free and characterized as non-explosible in line with ASTM E1226, Standard Test Method for Explosibility of Dust Clouds.

Höganäs has expanded its range of AM powders to include commercially pure titanium and Ti-6Al-4V. The company has also developed a nickel-free steel powder to reduce the environmental impact of end-use part production.

Producing powders for metal AM

Metal powders used for AM include nickel, cobalt, titanium, specialty steels, aluminum, tungsten, copper, and tantalum. Others are also available. These metals offer a wide range of metallurgical properties. Among them are resistance to thermal degradation, corrosion resistance, erosion resistance, strength and toughness, good conductivity, and low density.

Powders for metal AM are usually made using a gas atomization process. This involves vacuum induction melting and plasma atomization. Other processes include centrifugal atomization and water atomization (WA). Each of these processes has further subprocesses, depending on the raw material form and desired control over powder characteristics. Most of these atomization processes produce spherical powders that result in good powder density and reproducible particle size distribution.

Gas atomization blasts a stream of molten metal with a jet of neutral gas. This forms the metal into spherical particles.

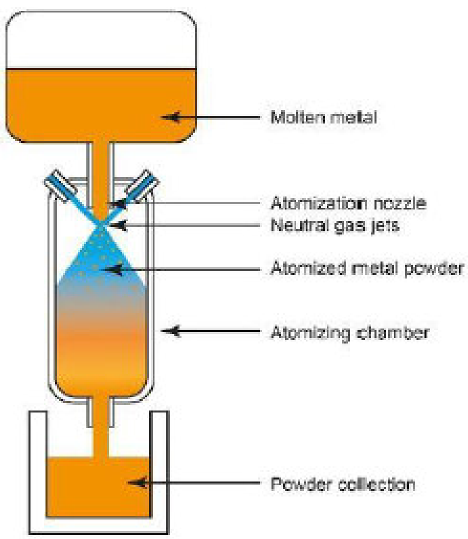


Fig. 123. Schematic diagram of a gas atomization system

Vacuum induction melting gas atomization is similar, but the process occurs in a vacuum, which minimizes oxidization of the metal powder. The following image shows spherical powder produced in a vacuum induction atomization process.

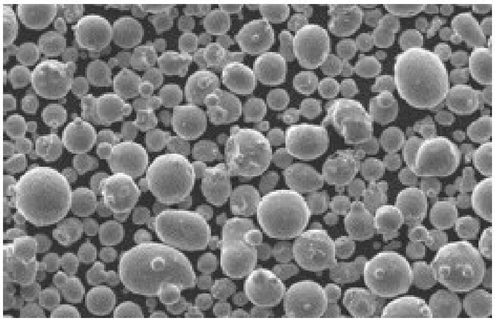


Fig. 124. Powder produced by vacuum induction melting, courtesy of Aubert & Duval

WA is the most common process for making metal powders for press-and-sinter and cold-isostatic-pressing applications. WA rapidly solidifies molten metal droplets using a water spray, resulting in an irregular, non-spherical particle shape.

WA powder is not generally used for AM. However, the technology could be advantageous due to its relatively low cost. Non-powder-bed AM processes, such as cold spray and DED, are less dependent on particle shape and are better suited for powder from WA.

The ideal powder shape for metal powder bed AM systems is spherical because it is beneficial for powder flowability and packing. Spherical particles form uniform, highly dense layers. This advantage applies equally to metal PBF and BJT systems. All powder bed AM systems work by spreading thin layers of powder before selectively fusing or binding each layer. Powder that spreads well improves part quality.

Typical powder structures to be controlled and minimized are:

- Irregular powder shape
- Agglomerates or satellites, which are small powder particles stuck to the surface of larger particles. They may impede spreading and/or "streak" the layer.
- Hollow powder particles with closed porosity. These particles can explode during the melting process or entrap gas in the part.

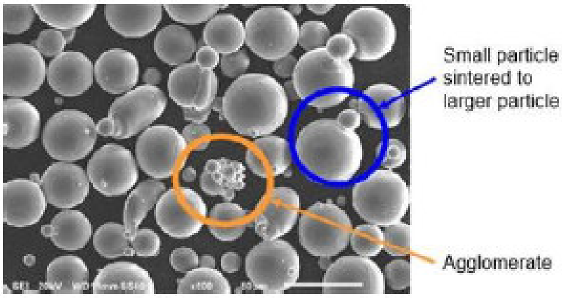


Fig. 125. Undesirable powder artifacts, courtesy of Renishaw

The particle size for PBF is typically in the range of 30–40 µm (0.0012–0.0016 in). Virtually all non-classified, unsieved powder distributions show a normal, bell-shaped curve when the logarithm of the particle size is plotted. Powder distributions contain many more small particles than large ones. Using a logarithm function transforms the curve to a bell-shaped normal distribution like the one shown in the following.

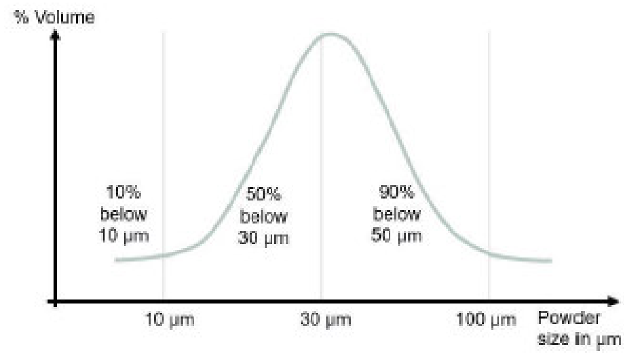


Fig. 126. Typical particle size distribution for laser PBF

Often, powder manufacturers "classify" powder by sieving. A sieve is a fine wire mesh with uniform, square openings of a given size. Powder poured through the sieve is separated into two lots: fine powder that passes through the sieve and coarser powder that does not pass through.

Average particle sizes of 100–150 µm (0.004–0.006 in) are commonly used for EBM and DED processes.

Mixing powders with different particle sizes is desirable if the smaller particles can fit between the larger ones in a powder bed. This increases the layer packing density.

Metal powders can be a health hazard if not handled properly. Among the factors to consider when working with metal AM powders are:

– Powder storage, handling, and aging: for almost all alloys, shielding gas, moisture control, and temperature control are important and strongly recommended.
– Powder recyclability: conditions of reuse of powders after AM build cycles.
– Health, safety, and environmental issues of metal powder: fine powders, such as aluminum and titanium, can explode.

The following table provides production processes used to make several types of metal powders.

Powder process	**Precursor material**	**Company**	**Process description**	**Alloys typically produced**							
				Ni	**Co**	**Fe**	**Ti**	**Al**	**Cu**	**W**	**Ta**
Chemical reduction processes											
MeltFree (TiRO)	$TiCl_4$, $AlCl_3$, VCL_2, M_xCl_y	Coogee Titanium	Kroll-like continuous Mg reduction				x				
FFC	M_xO_y	Metalysis	Electrochemical reduction, molten $CaCl_2$				x	Al-Sc			x
Armstrong	$TiCl_4$	Cristal Titanium	Chemical reduction by molten Na				x				

Powder process	Precursor material	Company	Process description	Alloys typically produced							
EMR Molten Salt Reduction	$TiCl_4$	CSIR	Hunter-like molten Na chemical reduction				x				
Meltless	Not disclosed	NextGen Alloys	Not disclosed				x				
Various - R&D	Chemicals	multiple	Chemical reduction				x	x		x	x
Traditional melting processes											
Gas Atomization	Elements, scrap	multiple	Vacuum melting + inert gas atomization	x	x	x					
Cold Wall Induction	Elements, scrap	multiple	Vacuum melting + inert gas atomization				x		x		
Atomization of mill products											
Plasma Wire Atomization	Cold drawn wire	multiple	Inert melting using plasma	x	x	x	x	x	x	x	x
EIGA	Exact length bar	multiple	Inert melting + gas atomization	x	x	x	x	x	x		
PREP	Precision straightened bar	multiple	Inert melting + centrifugal atomization	x	x		x				
Other											
Plasma Spheroidization	Irregular-shaped powder	Tekna	Inert melting in a RF plasma field	x	x		x	x	x	x	x
Mechanical Crushing	Sponge, thin-gauge scrap	multiple	Hydride-dehydride (HDH)				x				x

The following table provides the steps involved in common metal powder production processes. All of them include sieving, testing, and packaging.

Powder process	Step 1	Step 2	Step 3	Particle morphology
Chemical reduction processes				
MeltFree (TiRO)	M_xCl_y reduced by low-oxygen Mg powder in a fluidized bed reactor	Continuous vacuum distillation	N/A	Irregular, suitable for spheroidizing
FFC	M_xO_y electrochemical reduction in molten $CaCl_2$	Water wash to remove salt	N/A	Irregular
Armstrong	$TiCl_4$ reduced in a molten Na reactor	Water wash to remove salt	N/A	Irregular, dendritic
EMR Molten Salt Reduction	$TiCl_4$ reduced in a molten Na reactor	Water wash to remove salt	N/A	Irregular, spongy, or crystalline
Traditional melting processes				
Gas Atomization	Melt elements/scrap in a vacuum furnace	Atomize using inert gas via gas ring	Atomized droplets solidify in an inert atmosphere	Spherical

Powder process	Step 1	Step 2	Step 3	Particle morphology
Cold Wall Induction	Melt elements/scrap in a vacuum furnace	Atomize using inert gas via gas ring	Atomized droplets solidify in an inert atmosphere	Spherical
Atomization of mill products				
Plasma Wire Atomization	CD wire is fed into a plasma field	Wire is melted and atomized by plasma torches	Atomized droplets solidify in an inert atmosphere	Spherical
EIGA	Centerless ground bar is mounted then slowly fed into an induction coil	Bar end melts and is atomized using inert gas via a gas ring	Atomized droplets solidify in an inert atmosphere	Spherical
PREP	Precision straightened bar is rotated at high RPMs	Bar end is melted using a plasma torch; droplets are formed by centrifugal force	Atomized droplets solidify in an inert atmosphere	Spherical
Other				
Plasma Spheroidization	Irregular powder is fed into an RF plasma field	Particles are melted in the plasma field	Molten particles solidify in an inert atmosphere	Spherical
Mechanical Crushing	Sponge or thin-gauge scrap is heated in a furnace with a hydrogen atmosphere (hydrided)	The brittle metal is mechanically crushed	Crushed particles are heated and dehydrided in a vacuum furnace	Irregular shards

Metal powder pricing

The metal powder industry does not typically publish prices. Pricing transactions are held confidentially between producers and/or resellers and their customers. A rough estimate of typical AM powder prices for industrial metal powders ranges from about $70 to more than $360 per kg (2.2 lbs). Price differentials can be explained by one or more of the following:

- Value of the alloying elements
- Starting precursor materials
- Particle size differences
- Consumer-specified particle-size distribution
- Order quantity
- Producer costs

The intrinsic value of the elements that go into AM metal powders is similar to non-AM applications. If the use of scrap is prohibited, powder prices are typically higher than for applications that permit the use of scrap. Primary AM elements (i.e., aluminum, titanium, steel, etc.) are commodities and their costs vary, sometimes greatly, over time.

Precursor materials range from chemicals, scrap, and basic elemental metals, to wires, which have been hot worked from ingots and cold drawn. The cost of precursor materials directly affects the powder cost.

Several methods are available for creating metal particles, including atomization. Each method delivers a different range of particle sizes. This means the yield of powder suitable for specific applications also differs. This variable impacts the suitability of some atomization and particle-making processes for AM.

A second variable impacting prices occurs when an AM system can only use particles of a specific size range. This increase raises production costs of parts, which can be dramatic.

In general, the larger the order, the lower the price per kilogram. Processing costs, productivity, overhead, and profit requirements are price variables that differ from one powder producer to the next.

The following table includes estimated prices for 1 kg (2.2 lbs) of metal powder for AM. The prices can vary, sometimes greatly, depending on the quality of the product, quantity purchased, and other factors as discussed in this section.

Material	Price estimate (per kg)
AlSi10Mg aluminum alloy	$78
AlSi7 aluminum alloy	$74
316-L stainless steel	$88
17-4 PH stainless steel	$78
Maraging steel	$133
Ti-6Al-4V titanium alloy	$363
Pure Grade 2 titanium	$363
Inconel 718	$145
Inconel 625	$145

Source: Olaf Diegel

Composite materials

by Jon Baxendale

Composites consist of two or more different materials, typically in the form of a base material and a reinforcing material. The reinforcing material is typically either a particulate, discontinuous fiber, or continuous fiber. Many different types of reinforcing materials are used within AM including glass, carbon, aramids, and polymers.

Reinforcement materials are typically added to improve mechanical properties such as tensile strength, fracture toughness, and stiffness. However, some composite material combinations may be used for reasons other than mechanical performance. Examples are improving thermal or electrical characteristics, introducing multifunctionality, or creating 4D attributes.

Within fiber-reinforced composite AM parts, the fibers do not typically cross over from one layer to the next. Therefore, the improvements from the fibers are predominantly in the *x-y* plane and not in the *z* direction. Non-planar AM techniques can be used to overcome this to some extent. Achieving isotropic composite AM parts is an active area of R&D.

A wide range of base materials are available for composite AM processing, including thermoplastics, thermosets, metals, and ceramics. The scalability of composite AM is extensive, covering the use of nanoparticles in microscale printing up to producing entire buildings. All seven of the AM processes defined in the ISO/ASTM 52900 terminology standard have been used to produce composites in an R&D setting.

The number of AM hardware systems capable of producing composite parts is growing rapidly. Many MEX systems (with associated composite feedstock) are commercially available. The range of technologies being used to create composite AM parts is broadening with many system providers taking a multi-step processing approach. Examples include the Cast in Motion technology developed by Massivit, the Additive Fusion system from 9T Labs, and Additive Molding technology from Arris. Also, options exist for converting polymer matrix composites into ceramic matrix composites with additional processing steps.

Several approaches are being developed for 3D printing of thermoset-based composites. They include direct ink writing and ambient reactive extrusion. In some cases, the boundaries between AM and conventional composite manufacturing processes (e.g., automated fiber placement) are becoming blurred.

For MJT, particle loading is limited by flowability properties associated with jetting the mixture. For composites processed in VPP systems, unwanted spreading of the laser beam in the photopolymer can occur. Spreading is caused by internal reflections from particulate surfaces in the liquid. This can be eliminated by matching the indexes of refraction of the photopolymer and the particulate. Care must be taken with VPP systems to prevent unwanted settling of the reinforcement in the liquid.

For PBF, a reinforcement material is stirred into a base powder, such as nylon, to create a blend. This is possible for both particulate and chopped fiber reinforcement, but not for continuous fibers. The following image is an electric motorcycle's front nose, 3D printed with a carbon-fiber-reinforced nylon.

Fig. 127. Carbon-fiber-reinforced nylon motorcycle nose piece, courtesy of CRP Technology

Many MEX systems are capable of printing polymers containing chopped fibers. The fibers are brought into alignment as the feedstock is forced through the extrusion nozzle. MEX systems that can 3D print continuous fibers are available from Anisoprint, Markforged, and others. The continuous fibers are typically placed using mechanisms that operate independently of the base material deposition system.

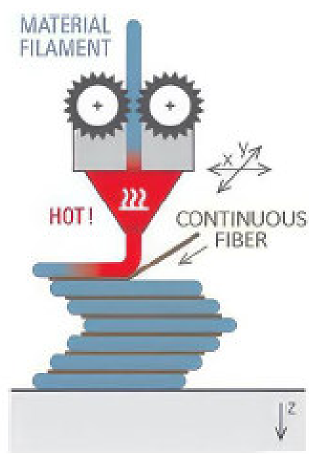


Fig. 128. Schematic of continuous-fiber composite MEX, courtesy of Steffen Ritter

For SHL processes, alternative approaches to creating composites are possible. The simplest method is to use sheets of composite materials that are cut to shape during the stacking process. Alternatively, the composite can be formed during stacking (e.g., by selectively depositing a base material between sheets of reinforcement material).

With BJT, composite parts can be produced in the same manner as PBF by introducing reinforcement material into a base powder. Alternatively, a combination of materials can be achieved by adding particles to the binder used during the process.

Composite parts can also be produced using DED processing methods. One approach is to use blown powder in which the powder constitutes a mix of materials to form a resultant composite part.

Hybrid metals

Nearly all PBF systems have been limited to part manufacturing in a single material. DED can support the printing of parts using two or more metals, although it is not common. Aerosint, a Desktop Metal company, has developed a recoater mechanism capable of selectively depositing multiple powders in a single build chamber. The multi-material layers are consolidated using thermal energy, such as a laser. This approach can potentially transform PBF from a single material process into one of multiple materials.

Fig. 129. Multi-metal heat exchanger, courtesy of Aerosint and Aconity

The ultrasonic SHL process from Fabrisonic can produce metal hybrid parts in two distinctly different ways. First, metal foil pairs, such as copper and aluminum, can be used to produce a single part. Second, special materials can be embedded between layers to produce metal parts with unique properties. For example, nickel-titanium fibers can be embedded between layers of aluminum. This produces a composite part with a coefficient of thermal expansion that is considerably lower than aluminum without the fibers.

Fig. 130. Rocket fuel pipes with embedded fiber-optic sensors, courtesy of Fabrisonic

The Fabrisonic process has been used to create more than 70 different paired metal combinations. Aluminum-copper, aluminum-iron, and aluminum-titanium are routinely joined. More exotic combinations are also possible, such as tantalum-iron, silver-gold, and nickel-stainless steel.

Impact Innovations specializes in cladding cylinders and pipes with dissimilar materials in a wide range of sizes using a cold spray process. The part in the following image was made from copper and Inconel, a nickel-based alloy.

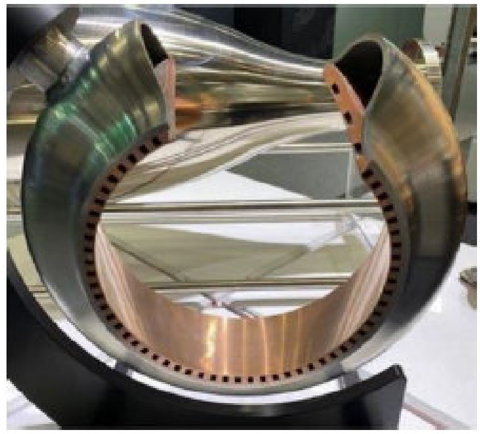


Fig. 131. Inlet manifold of a combustion chamber made from copper and nickel alloys, courtesy of Impact Innovations

Materials for metal casting

Materials specifically for metal-casting processes are available for AM. The two primary categories are investment and sand casting.

AM parts can be used as wax patterns for investment casting, which can save labor and time compared to producing them by hand. Patterns made by AM can include optimized gating and riser locations, saving further assembly. Investment casting materials melt or burn out of the shell with minimal residue or ash. AM material producers offer several photopolymers and thermoplastic filaments for investment casting.

MJT systems from Solidscape, a Prodways company, can create investment-casting patterns for jewelry. DWS and ETEC offer photopolymers that are burned out before casting. PMMA used in Voxeljet machines can also be used for casting patterns. EOS offers PrimeCast 101, a polystyrene used in its PBF machines. 3D Systems offers QuickCast, a stereolithography technique used to produce patterns that are mostly hollow.

Fig. 132. Printed wax pattern (left) and finished ring (center and right), courtesy of Sasha Primak and Solidscape

Important parts for expendable-mold sand casting are the cope (top half of mold), drag (bottom half of mold), and cores. For metal casting, these mold parts are used once because they are destroyed in the process of retrieving the metal casting. AM has been used to produce all three components, but particularly for cores due to their innate complexity. ExOne and Voxeljet offer foundry sand for their large BJT systems. Longyuan and Shaanxi Hengtong also offer foundry sand for their PBF systems.

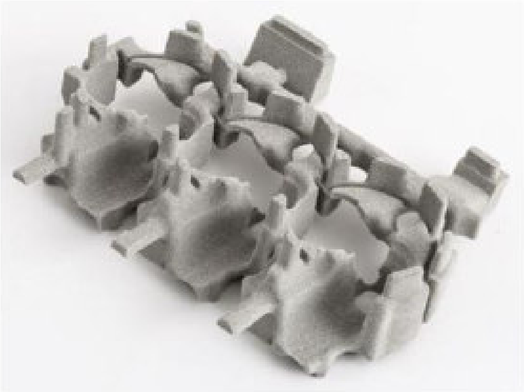


Fig. 133. Sand core made by AM, courtesy of Voxeljet

Refer to the supplemental document named castmetal2023.pdf for more depth and breadth on cast metal parts.

Ceramics and other materials

Ceramic materials and blends are offered by a growing number of companies. 3Dceram Sinto, Admatec, Lithoz, Prodways, and Tethon 3D offer photopolymers filled with ceramic particles. A secondary furnace cycle burns out the binder and sinters the ceramic, resulting in shrink of 15–30%, depending on the material and process. BJT systems from Concr3de and ExOne produce glass and ceramic parts.

NanoParticle Jetting from XJet produces zirconia and alumina parts. Part density is reported to be 99.9% after a furnace cycle that results in shrink of 16%.

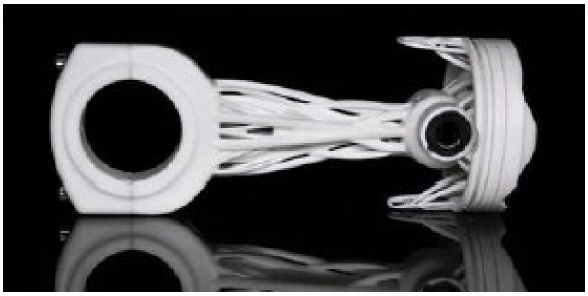


Fig. 134. Ultracar piston and connecting rod, courtesy of XJet

Biocompatible materials are a growing area of interest. Some metals, such as titanium alloy Ti-6Al-4V, are commonly implanted in human patients. Polymers, such as PEEK and polyetherketoneketone (PEKK), are also implanted. ETEC lists several biocompatible materials for its 3D-Bioplotter system.

Fig. 135. PEEK spinal cage, courtesy of Bond3D

Graphene reinforcement can improve mechanical strength, thermal conductivity, and electrical conductivity of AM polymers, particularly thermoplastics. Graphene-laden AM materials have been used to create durable electronic sensors and even advanced concretes for railway structures.

Fig. 136. 3D-printed graphene-reinforced retaining wall, courtesy of Costain, Skanska, and Strabag

Third-party material producers

Many companies produce AM materials. Some sell feedstock directly to AM system manufacturers, who in turn brand it as their own and supply it to customers. In many cases, these agreements are not disclosed to the public. Other producers supply AM materials directly to the end user. Historically, this group of third-party material producers has been small. However, it has grown rapidly in recent years, particularly in the metal powder segment.

Open vs. closed material business models

Material sales can be an important source of recurring revenue for AM system manufacturers. These companies are reluctant to lose that revenue stream to others. The machines they produce and sell can have physical, electronic, or software locks to prevent the use of "unauthorized" materials.

Some system manufacturers have developed and maintained patents and trade secrets, and at times pursued litigation to defend them. The intent is for customers to use only their materials. These manufacturers often follow the practice of voiding warranties or not honoring maintenance agreements when machines have been operated with alternatively sourced materials. A few third-party service providers offer equipment maintenance and repair services to customers.

In the early years of the AM industry, system manufacturers performed nearly all development work internally by necessity. This included mechanical design, software development, and materials R&D. As a result, a closed-architecture model ensued, and few third-party materials were available. Today, the closed-architecture model is still present for some AM machines and materials. Other companies have embraced partnerships and agreements with outside material producers and vendors.

For metal AM, the open-architecture material model has taken precedence. This may be partly because metal AM has developed in parallel with the adoption of AM for production applications. Large customers require multiple sources of raw materials to ensure the viability of their production supply chain. The cost of the materials is also critical because these systems are often used for full-scale manufacturing. If the material is too expensive, the use of AM for production is not feasible.

Third-party producers

The following tables list third-party companies that produce and sell materials for AM systems. Some companies produce AM materials but only sell 3D-printed parts made from the material and not the material itself. These companies are excluded from the tables.

The first table includes producers of non-metal AM materials, most of which are polymers. The second table lists producers of metal powder for AM. These powders are typically formulated for metal PBF machines, but increasingly stretch to metal BJT. The material producers are listed alphabetically in each table. These tables are not exhaustive, but they include most of the major companies in this business.

Non-metal powder producers

Company	Technologies	Website
3D Resin Solutions	VPP	www.3drs.com
3D4Makers	MEX	www.3d4makers.com
3DFuel	MEX	www.3dfuel.com
3DXTech	MEX	www.3dxtech.com
Adaptive3D	VPP	www.adaptive3d.com
Additive Elements	MJT	www.additive-elements.de
Allied Photopolymers	VPP	www.alliedphotopolymers.com
Arkema	PBF, VPP	www.arkema.com
Barlog Gruppe	MEX	www.barlog.de
BASF	MEX, PBF	www.basf.com
Braskem	MEX	www.braskem.com
c2renew	MEX	www.c2renew.com
Canada Powder	BJT	www.canadapowder.com

Company	Technologies	Website
Chromatic 3D Materials	MEX	www.c3dmaterials.com
Clariant	MEX	www.clariant.com
ColorFabb	MEX	www.colorfabb.com
Copper3D	VPP	www.copper3d.com
Covestro	MEX, PBF	www.covestro.com
CRP Technology	PBF	www.crptechnology.com
Detax	VPP	www.detax.de
Diamond Plastics	PBF	www.dpcpipe.com
Dreve	VPP	www.dreve.de
DSM Somos	MEX, VPP	www.dsm.com
DuPont	MEX	www.dupont.com
Emery Oleochemicals	MEX	www.emeryoleo.com
Ensinger	MEX	www.ensingerplastics.com
Esun	MEX	www.brightcn.net
Evonik	PBF	www.evonik.com
Fenner Inc.	MEX	www.ninjatek.com
Filament PM	MEX	www.filament-pm.com
Filaticum	MEX	www.filaticum.com
Filkemp	MEX	www.filkemp.com
Fillamentum	MEX	www.fillamentum.com
FormFutura	MEX	www.formfutura.com
Gehr	MEX	www.gehr.de
Graphite Additive Manufacturing	PBF, VPP	www.graphite-am.co.uk
Henkel Adhesive Technologies	VPP	www.henkel.com
Huntsman	MEX, PBF, VPP	www.huntsman.com
Infinite	MEX	www.weareinfinite.tech
iSquared	MEX, MJT, VPP	www.isquared.eu.com
Kuraray	VPP	www.kuraray.com
Lehmann & Voss & Co.	MEX, PBF	www.luvacom.de
Matter Providers	DED	www.matterproviders.com
MCPP Netherlands	MEX	www.mcpp-3dp.com
Microfol Compounding	PBF	www.microfol.de
Nanoe	MEX	www.nanoe.com
NatureWorks	MEX	www.natureworksllc.com
Nefilatek	MEX	www.nefilatek.com
NextDent-Vertex	VPP	www.nextdent.com
Poligraf	MEX	www.papierdoplotera.com
Polymaker	MEX	www.polymaker.com
Recreus Industries	MEX	www.recreus.com
Rosa Filaments	MEX	www.rosa3d.pl
SABIC	MEX	www.sabic.com

Company	Technologies	Website
Sailner	VPP	www.sailner.com
Solvay	MEX, PBF	www.solvay.com
Sonnaya Ulitka	VPP	www.spotamaterials.com
Stronghero3D	MEX	www.stronghero3d.com
Taulman3D	MEX	www.taulman3d.com
Techmer PM	MEX	www.techmerpm.com
Tethon3D	VPP	www.tethon3d.com
The Dow Chemical Company	MEX	www.dow.com
TIGER Coatings	PBF	www.tiger-coatings.com
Toray Industries	PBF	www.toray.com
Univar Solutions	MEX	www.univarsolutions.com
UPM	MEX	www.upm.com
Victrex	MEX	www.victrex.com
Virtual Foundry	MEX	www.thevirtualfoundry.com
Wacker Chemie	MEX	www.wacker.com
Winkle	MEX	www.winkle.shop
Xerox	MEX	www.xerox.com
Xioneer	MEX	www.xioneer.com
	Metal powder producers	
Company		**Website**
6K		www.6kinc.com
Advanced Laser Materials		www.alm-llc.com
Alleima		www.alleima.com
Alloyed		www.alloyed.com
Alpha Powders		www.alphapowders.eu
Amepere Alloys		www.amperemetalpowders.com
Arconic		www.arconic.com
ATI Specialty Materials		www.atimetals.com
Atomizing Systems Ltd.		www.atomising.co.uk
Aubert & Duval		www.aubertduval.com
Carpenter Technology		www.carpenteradditive.com
Chung Yo Materials		www.cymaterials.com.tw
Circle Metal Powder		www.cmpowder.com
CVMR		www.cvmr.ca
Eckart		www.tls-technik.de
Elementum 3D		www.elementum3d.com
Equispheres		www.equispheres.com
Eutectix		www.eutectix.com
Fehrmann		www.fehrmann-materials.com
GKN		www.gknpm.com
Global Tungsten & Powders Corp. (Plansee)		www.globaltungsten.com
Graphite Additive Manufacturing		www.graphite-am.co.uk

Company	Website
H.C. Starck	www.hcstarck.com
Headmade Materials	www.headmade-materials.de
Heraeus	www.heraeus.com
Höganäs AB	www.hoganas.com
HRL Labs	www.hrl.com
IMR Metal Powder	www.imr-group.com
Johnson Matthey	www.matthey.com
Kymera International	www.kymerainternational.com
m4p material solutions	www.metals4printing.com
MacLean-Fogg	www.macleanfoggcs.com
Matrix Nano	www.matrixnano.co.in
Metalysis	www.metalysis.com
Mimete	www.mimete.com
MolyWorks	www.molyworks.com
Next Gen Alloys	www.ng-steel.com
Nordic Metals	www.nordicmetals.com
Oerlikon	www.oerlikon.com
Osaka Titanium Technologies	www.osaka-ti.co.jp
Pint	www.pint-innovative.com
Powder Alloy Corporation	www.powderalloy.com
Praxair Surface Technologies	www.praxairsurfacetechnologies.com
Pyrogenesis	www.pyrogenesis.com
QuestTek Innovations LLC	www.questek.com
Reade	www.reade.com
Schmelzmetall	www.schmelzmetall.com
SentesBIR	www.sentes-bir.com
Sino-Euro	www.c-semt.com/
Steward Advanced Materials	www.stewardmaterials.com
Tekna	www.tekna.com
TIMET	www.timet.com
Toyal	www.toyala.com
Tronox	www.tronox.com
Uniformity Labs	www.uniformitylabs.com
United States Metal Powders	www.usmetalpowders.com
UTRS	www.utrs.com
Valimet	www.valimet.com
VBN Components	www.vbncomponents.com
VDM Metals	www.vdm-metals.com
Wolfmet Tungsten Alloys	www.wolfmet.com
Z3DLAB	www.z3dlab.com

Source: Wohlers Associates

Materials database

Senvol maintains a public database of AM systems and materials. The company tracks the producers of materials and the products they offer. If a company offers five grades of stainless steel powder, each in four particle-size distributions, they are counted as 20 individual products. AM materials can be searched at www.senvol.com. The data is compiled to reflect year-end figures from 2017 through 2022 and filtered to omit discontinued products as of December 2022.

Materials by process

The following table shows the number of material products for each of the seven AM process categories and six types of materials. Some metal powders are available for multiple processes such as PBF, DED, and BJT. To avoid replication, these materials are counted under PBF because it is the more commonly used process.

	BJT	DED	MEX	MJT	PBF	SHL	VPP	Total
Ceramic	3	1	6	-	1	-	29	40
Composite	7	4	192	-	77	2	12	294
Sand	5	-	-	-	-	-	-	5
Wax	-	-	1	3	-	-	14	18
Metal	28	88	23	-	964	18	4	1125
Polymer	3	-	668	84	173	-	760	1,688
Total	46	93	890	87	1,215	20	819	3,170

Source: Senvol

The most diverse offering of materials is for metal PBF, by a large margin, followed by polymer VPP and polymer MEX.

Material producers and products

Senvol tracks companies that supply AM materials. They include AM system manufacturers and third-party material producers. The total number of suppliers is shown by year in the following graph. All data used to produce the following charts was taken at the end of each year. The number of material suppliers has grown consistently from 2017 to 2022. From 2021 to 2022, the number of suppliers increased by 16%.

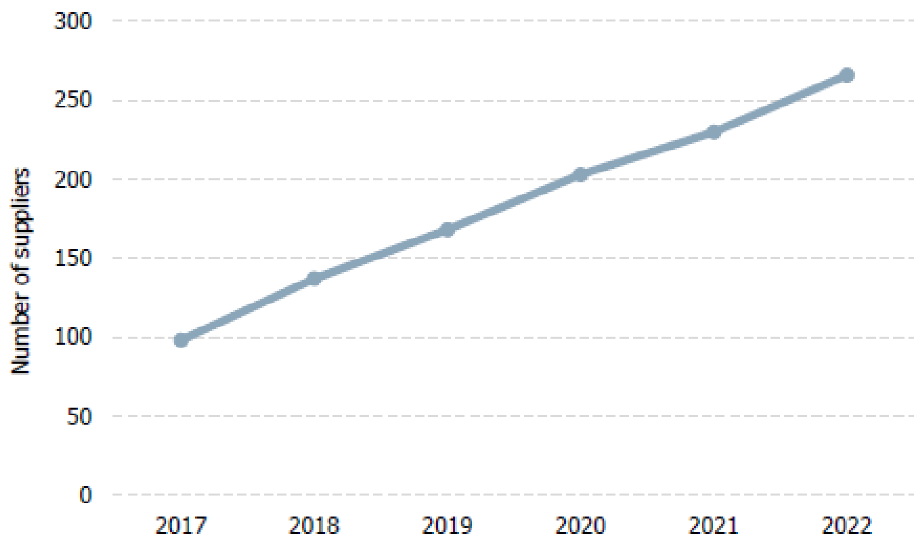


Fig. 137. Total number of tracked material suppliers by year; source: Senvol

The following chart shows the total number of commercially available products.

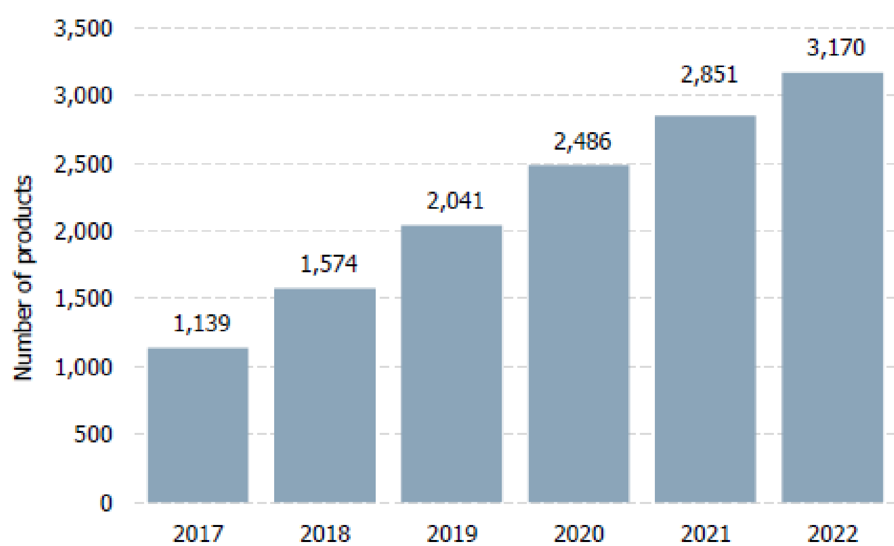


Fig. 138. Total number of commercially available products; source: Senvol

In 2022, 88% of commercially available AM materials were polymers and metals, which represent 53% and 35%, respectively. The largest growth in material products for AM was in composites at 16%. The largest total increase in products was in polymers with 177 new materials in 2022. Ceramic, sand, and wax represent specialized applications and systems and are only available from a limited selection of suppliers. The following table provides a further breakdown of the data used to produce the previous chart.

	2017	2018	2019	2020	2021	2022
Ceramic	24	23	33	36	37	40
Composite	100	138	175	219	254	294
Metal	498	693	844	988	1,026	1,125
Polymer	496	700	969	1,222	1,511	1,688
Sand	5	5	5	5	5	5
Wax	16	15	15	16	18	18

Source: Senvol

The following chart shows metal products available for AM over the past five years. They include filaments, powders, sheets, and wire stock.

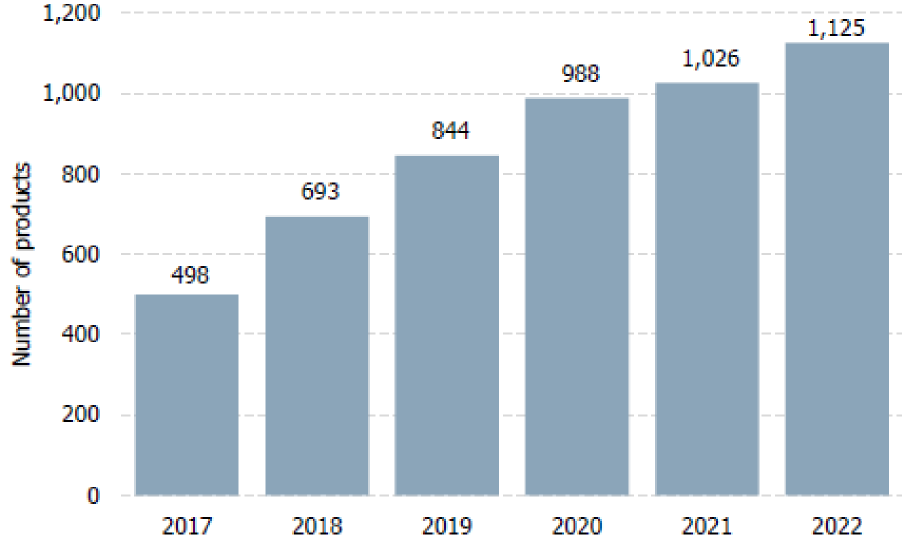


Fig. 139. Total number of metal products available for AM by year; source: Senvol

Nickel-based alloys, steels, and titanium products represented 66% of the available metals for AM in 2022. The "Other" category includes iron, precious metals, and refractory metals. Applications for these metals are increasing, but the materials are available from a limited number of suppliers. The data used to create the previous chart is presented in the following table.

	2017	2018	2019	2020	2021	2022
Aluminum	49	78	104	115	121	130
Cobalt	39	56	58	66	71	74
Copper	9	16	25	34	37	43
Nickel	105	158	177	205	209	228
Steel	132	177	227	269	281	308
Titanium	118	142	175	199	203	209
Other	46	66	78	100	104	133

Source: Senvol

The following chart shows growth trends in the most used thermoplastic products for AM, primarily polymers used in MEX and PBF systems.

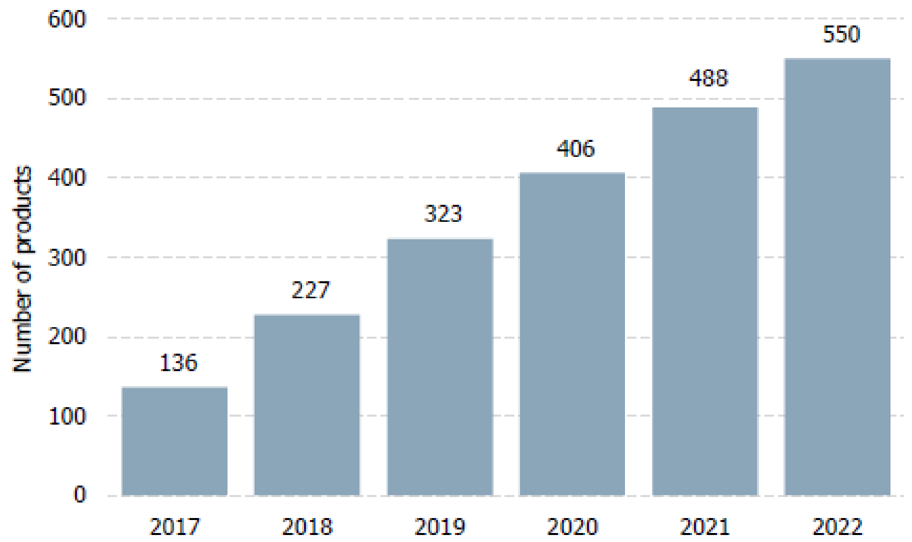


Fig. 140. Total number of polymer products available for AM by year; source: Senvol

PA, also known as nylon, dominates the thermoplastics market due to the growing number of PBF machines and applications that use these powders. They include many grades of PA, such as PA6, PA11, and PA12, with the latter being the most common. PA has also proven useful in MEX systems.

TPU is an elastomer used with MEX and PBF systems. Its popularity has increased due to newfound use in flexible and soft products such as helmet liners, shock absorbers, and other parts that require high material toughness. Overall, polymers for MEX and PBF are expected to expand and diversify over the coming years. The data used to create the previous chart is broken out by material in the following table.

	2017	**2018**	**2019**	**2020**	**2021**	**2022**
ABS	15	25	38	54	63	69
PA	67	85	103	110	128	142
PC	9	14	18	20	26	26
PEEK	6	11	17	19	19	22
PEI	7	13	16	17	21	22
PETG	8	12	20	27	36	41
PLA	8	25	40	62	78	98
PP	4	10	18	27	35	41
TPE	2	7	13	19	20	20
TPU	10	25	40	51	62	69

Source: Senvol

PART 3: INDUSTRY GROWTH

Overall, the additive manufacturing (AM) industry showed steady growth in 2022, with most system manufacturers of all sizes experiencing increased machine sales.

In 2022, AM system manufacturers and service providers reported an increase in revenue from services. Wohlers Associates believes that when system sales are at risk of declining, manufacturers put more energy into increasing sales of services.

The average annual growth rate of worldwide revenues produced by all AM products and services over the past 34 years is 25.6%. The average annual growth over the past four years (2019–2022) is 16.6%. The industry continues to offer tremendous untapped potential.

Revenue from AM worldwide

Overall, AM products and services worldwide grew by 18.3% to $18.027 billion in 2022. This compares to growth of 19.5% to $15.244 billion in 2021.

Growth of 18.3% in 2022 is based on data received from 274 service providers, AM system manufacturers, and producers of third-party materials worldwide. A company experiencing a year of poor performance may be less likely to respond to requests for information on how they are doing. However, respondents provided both positive and negative comments and evaluations.

The 10 largest system manufacturers represented about $2.721 billion (15.1%) of the entire AM industry in 2022. This shows the influence major companies in AM are having on industrywide growth.

The $18.027 billion industrywide estimate includes revenue from the primary AM market. This segment consists of all products and services directly associated with AM processes. Products include AM systems, materials, and aftermarket products, such as software and lasers. Services include revenue generated from parts produced on AM systems by independent service providers. It also includes system maintenance contracts, training, seminars, conferences, expositions, advertising, publications, contract research, and consulting services.

The global estimate of $18.027 billion excludes money spent on AM inside companies such as Airbus, GM, Nike, Raytheon, and thousands of others, both large and small. It excludes the value of research, development, prototyping, tooling, and production with AM at these companies and at universities and national laboratories. The global estimate omits the value of AM parts produced by the original equipment makers (OEMs) of automobiles, aircraft, healthcare products, consumer products, and so on. The value they are producing with AM adds up to a large amount, but it is impossible to quantify.

The $18.027 billion also excludes venture capital, private equity, and other investments in AM-related companies in 2022. Details on many of these investments are found in this report.

Products and services

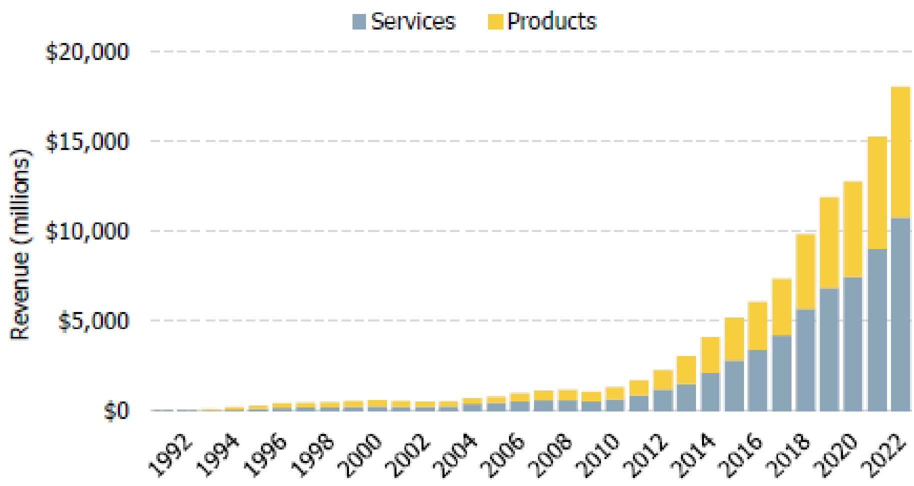
Worldwide revenues from AM products were an estimated $7.289 billion in 2022, an increase of 17.0% from the $6.229 billion produced in 2021. This segment grew by 17.5% in 2021, 5.1% in 2020, and 22.3% in 2019.

Total revenues from AM systems were an estimated $3.795 billion in 2022. This represents only the systems themselves and does not include maintenance agreements, replacement parts for these systems, and software upgrades. This represents an increase of 11.0% over $3.417 billion produced in 2021. System sales increased 13.4% in 2021, 1.0% in 2020 and 14.7% in 2019.

AM services grew to an estimated $10.738 billion in 2022, an increase of 19.1% from $9.015 billion in 2021. This market segment grew by 20.9% in 2021, 9.2% in 2020 and 20.3% in 2019. In 2022, revenue from service providers was $7.508 billion, which represents 69.9% of the total $10.738 billion in AM service revenues.

The following graph provides revenues (in millions of dollars) for AM products and services worldwide. The lower (gray) segments of the bars represent services, while the upper (yellow) segments represent products. Neither category includes secondary parts or processes, such as molded parts and castings. The industry has experienced significant growth in the past 10 years, expanding by more than 7.9 times over this period.

Fig. 141. Overall AM industry revenues; source: Wohlers Associates



Growth percentages

The following table provides annual revenue growth percentages. Revenues from services were unavailable prior to 1994, the year that Wohlers Associates began tracking this information.

Year	Overall % growth/decline	Products % growth/decline	Services % growth/decline
1988	–	–	–
1989	153.2%	153.2%	–
1990	25.6%	25.6%	–
1991	32.7%	32.7%	–
1992	18.5%	18.5%	–
1993	–	28.1%	–
1994	99.7%	59.4%	139.4%
1995	48.8%	58.8%	42.3%
1996	42.6%	41.0%	43.9%
1997	7.5%	10.6%	5.3%
1998	4.6%	6.3%	3.3%
1999	13.9%	14.6%	13.3%
2000	11.5%	2.1%	18.9%
2001	-10.5%	-1.7%	-16.4%
2002	-10.0%	-0.9%	-17.2%
2003	9.2%	15.2%	3.5%
2004	33.3%	48.3%	17.5%
2005	14.6%	10.0%	20.9%
2006	21.7%	20.0%	23.7%
2007	16.0%	14.7%	17.5%
2008	3.7%	0.0%	7.9%
2009	-9.8%	-13.2%	-6.2%
2010	24.1%	22.9%	25.3%
2011	29.4%	28.0%	30.7%
2012	32.7%	28.8%	36.4%
2013	33.4%	41.3%	26.3%
2014	35.2%	31.6%	38.9%
2015	25.9%	18.4%	33.0%
2016	17.4%	12.9%	21.2%
2017	21.0%	17.4%	23.8%
2018	33.5%	31.6%	35.0%
2019	21.2%	22.3%	20.3%
2020	7.5%	5.1%	9.2%
2021	19.5%	17.5%	20.9%
2022	18.3%	17.0%	19.1%

Source: Wohlers Associates

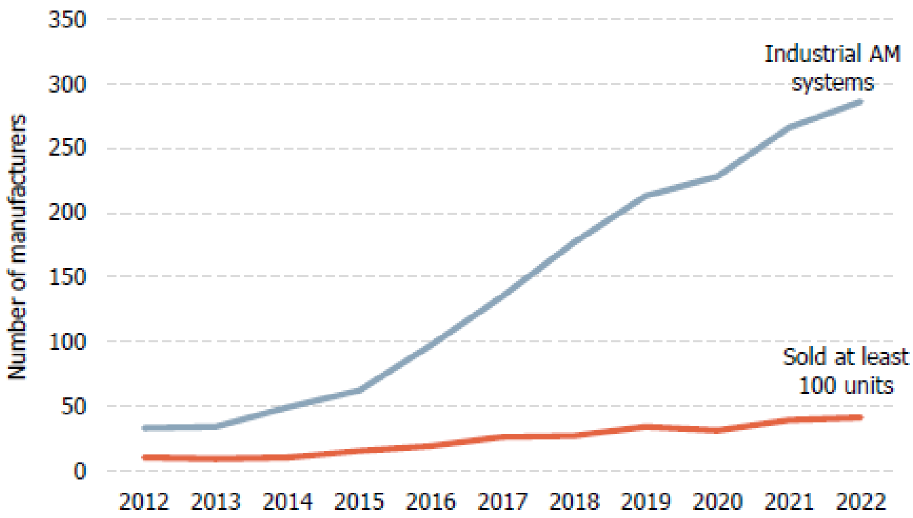
System manufacturers

Industrial AM systems have been tracked for 28 consecutive years by Wohlers Associates. Excluded from this section are systems that sell for less than $5,000, often referred to as "desktop" or "low-cost" 3D printers. They are covered in the section titled "Desktop 3D printers."

The rapid proliferation of AM system manufacturers has accelerated in recent years. In 2022, Wohlers Associates tracked 286 manufacturers who produced and sold industrial AM systems worldwide. This is an increase of 20 manufacturers (7.5%), compared to 2021. Since 2012, the number of industrial system manufacturers has grown by more than 1,100%.

The top (gray) line in the following graph shows the number of manufacturers of industrial AM systems. The bottom (red) line shows the number of manufacturers that sold a minimum of 100 machines annually. In 2022, 41 companies sold at least 100 systems, compared to 39 in 2021.

Fig. 142. Growth in AM system manufacturers; source: Wohlers Associates



The 286 system manufacturers are spread across six continents, as shown in the following table. The number of manufacturers in China remained steady at 37 in 2022. The number of manufacturers in the U.S. decreased from 59 in 2021 to 53 in 2022.

Country	# of system manufacturers	Country	# of system manufacturers
United States	53	Brazil	3
China	37	Canada	3
Germany	37	South Africa	3
South Korea	16	Switzerland	3
Netherlands	13	Belgium	2
Austria	11	Denmark	2
Italy	10	Finland	2
Japan	10	Slovenia	2
France	8	Argentina	1

Country	# of system manufacturers	Country	# of system manufacturers
Israel	8	Columbia	1
Spain	8	Czech Republic	1
India	7	Iran	1
Poland	7	Latvia	1
Australia	6	Liechtenstein	1
Turkey	6	Luxembourg	1
Russia	5	Portugal	1
Taiwan	5	Romania	1
United Kingdom	5	Singapore	1
Sweden	4		

Source: Wohlers Associates

R&D spending

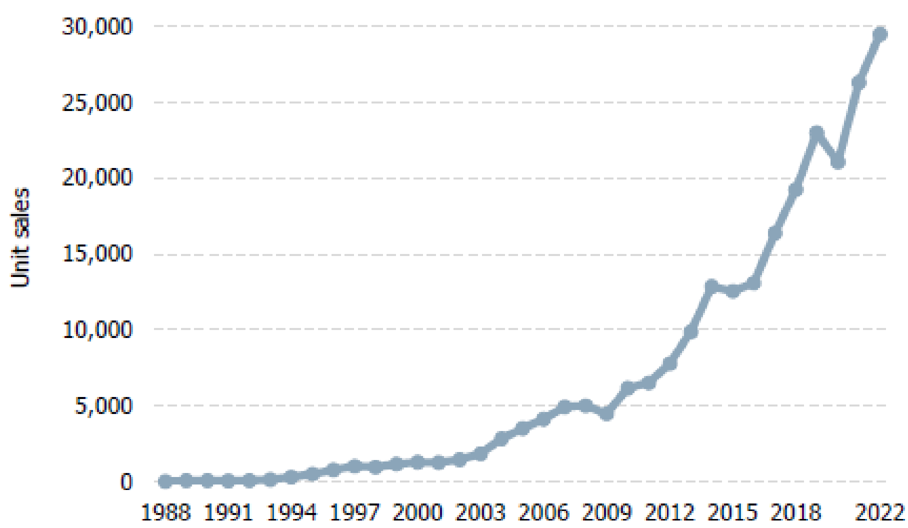
Eighty-seven system manufacturers reported research and development (R&D) spending. In 2022, these companies spent an average of 30.6% of their annual revenue on R&D. This is compared to 36.8% in 2021, 36.3% in 2020, and 38.6% in 2019. These relatively high percentages are likely due to the many relatively young manufacturers that responded to the survey. They are still in an early development phase and spending more on R&D than more mature companies.

Unit sales

In 2022, an estimated 29,446 industrial systems were sold. This total represents growth of 12.1% from the 26,272 systems sold in 2021. The year 2021 saw growth of 24.9% from 2020 with 26,272 systems sold, while 2020 saw a decline of 8.4% from 2019.

The following chart shows industrial system sales from 1988 through 2022.

Fig. 143. Industrial AM system sales; source: Wohlers Associates



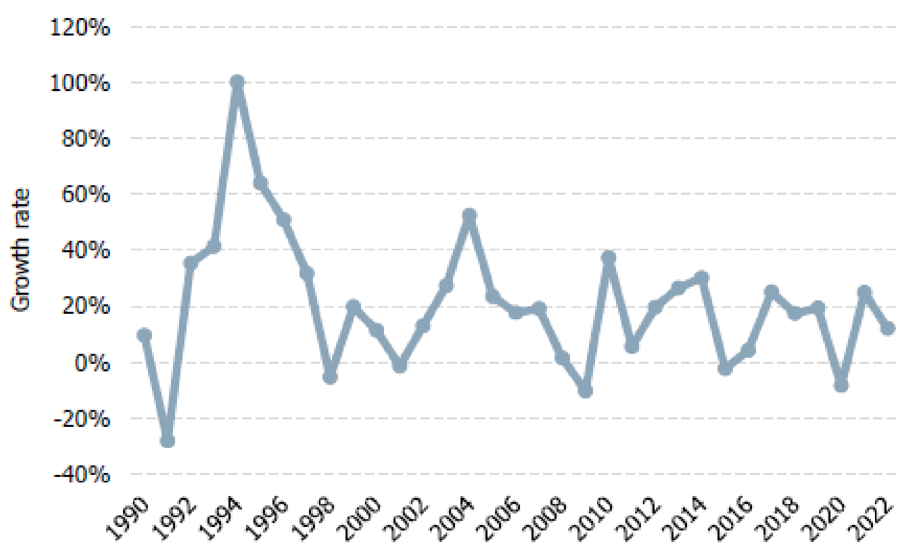
The following table gives the unit sales growth rate of industrial AM systems by year. As you can see, growth has varied greatly over the history of the industry. The average annual growth rate from 1990 through 2022 is 20.9%. The average growth was 12.0% over the past four years (2019–2022).

Year	Growth	Year	Growth
1989	205.9%	2006	17.7%
1990	9.6%	2007	19.1%
1991	-28.1%	2008	1.5%
1992	35.4%	2009	-10.3%
1993	41.4%	2010	37.3%
1994	103.8%	2011	5.6%
1995	64.1%	2012	19.6%
1996	50.9%	2013	26.6%
1997	31.7%	2014	30.2%
1998	-5.3%	2015	-2.3%
1999	19.8%	2016	4.2%
2000	11.4%	2017	25.1%
2001	-1.4%	2018	17.5%
2002	13.0%	2019	19.4%
2003	27.3%	2020	-8.4%
2004	52.5%	2021	24.9%
2005	23.5%	2022	12.1%

Source: Wohlers Associates

The following shows these growth rates in the form of a graph. It reflects the fluctuation of system sales over the history of the AM industry.

Fig. 144. Industrial AM system growth rate; source: Wohlers Associates

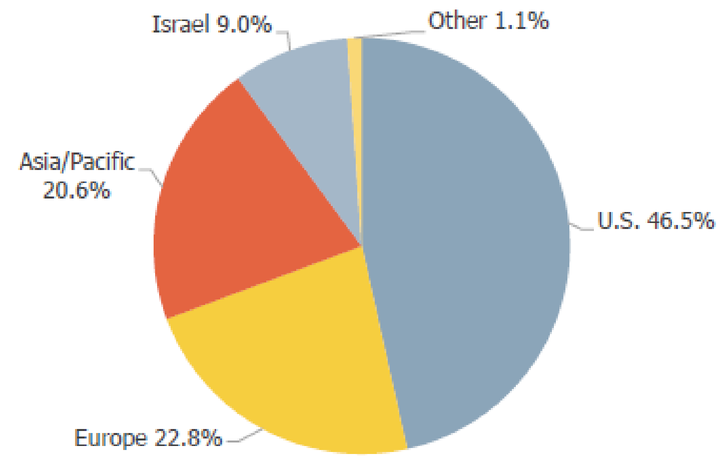


Systems sold by region

The following chart shows the percentage share of industrial AM systems sold in 2022 by companies headquartered in different geographic regions. They are systems that are sold from these regions of the world and not necessarily installed within them. The installation of systems by geographic region can be found at the beginning of part 5.

For 2022, the U.S. represented 46.5% of unit sales, an increase from the 45.5% share in 2021. The share of unit sales from Europe in 2022 declined to 22.8% from 23% in 2021. It increased in the Asia/Pacific region to 20.6% from 17.2% in 2020. Israel's share declined from 12.3% to 9.0% in 2022. These percentages represent unit sales and not revenues.

Fig. 145. Industrial AM systems sold by region; source: Wohlers Associates



Cumulative sales

The following table shows the cumulative number of industrial AM machines sold each year from 1988 through 2022. The "Cumulative unit sales" column gives the total number of machines sold since Wohlers Associates first started tracking unit sales in 1988.

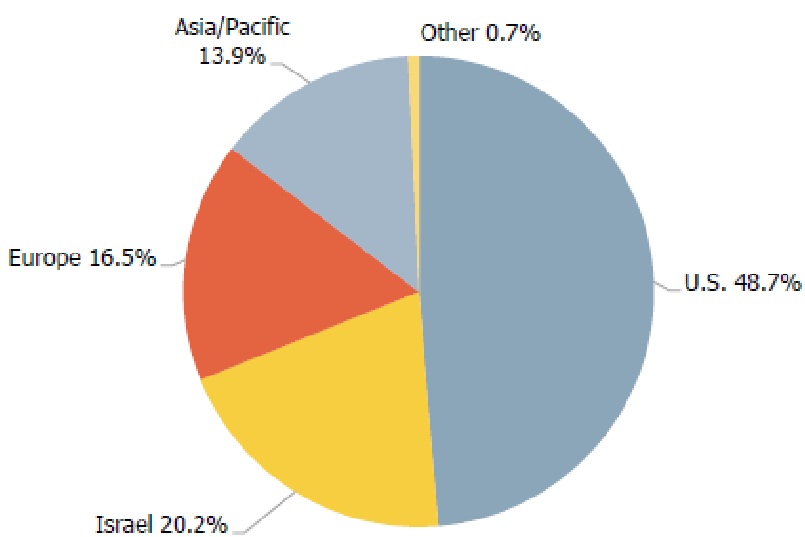
Year	Cumulative unit sales	Growth over previous year	Year	Cumulative unit sales	Growth over previous year
1988	34		2006	21,946	23.3%
1989	138	305.9%	2007	26,891	22.5%
1990	252	82.6%	2008	31,908	18.7%
1991	334	32.5%	2009	36,407	14.1%
1992	445	33.2%	2010	42,585	17.0%
1993	602	35.3%	2011	49,111	15.3%
1994	922	53.2%	2012	56,914	15.9%
1995	1,447	56.9%	2013	66,792	17.4%
1996	2,239	54.7%	2014	79,651	19.3%
1997	3,282	46.6%	2015	92,208	15.8%
1998	4,270	30.1%	2016	105,292	14.2%
1999	5,454	27.7%	2017	121,661	15.5%

Year	Cumulative unit sales	Growth over previous year	Year	Cumulative unit sales	Growth over previous year
2000	6,773	24.2%	2018	140,902	15.8%
2001	8,074	19.2%	2019	163,872	16.3%
2002	9,544	18.2%	2020	184,901	12.8%
2003	11,415	19.6%	2021	211,173	14.2%
2004	14,269	25.0%	2022	240,619	13.9%
2005	17,795	24.7%			

Source: Wohlers Associates

The following chart shows, by region, the percentage of total cumulative industrial AM systems sold from 1988 through 2022. U.S. system manufacturers are responsible for 48.7% of all industrial AM machines sold, down from 49.0% in 2021. Israel's share decreased from 21.8% to 20.2%. Europe's share increased from 15.6% to 16.5%, and Asia's share increased from 12.9% to 13.9%.

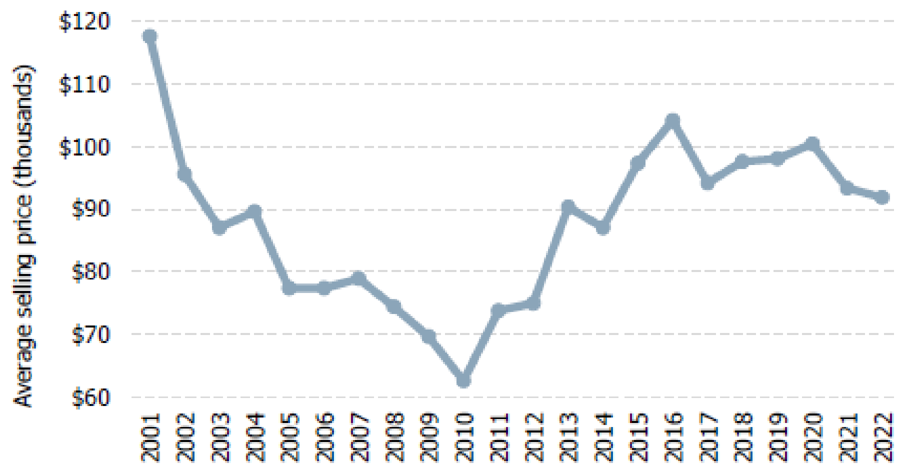
Fig. 146. Industrial AM systems sold by region – cumulative; source: Wohlers Associates



Average selling price

The average selling price (ASP) of an industrial AM system was $91,927 in 2022. This compares to $93,404 in 2021, $100,510 in 2020, and $98,105 in 2019, as shown in the following graph. (The values are in thousands of dollars.) Desktop 3D printers are not included in this ASP calculation.

Fig. 147. Average selling price of industrial AM systems; source: Wohlers Associates



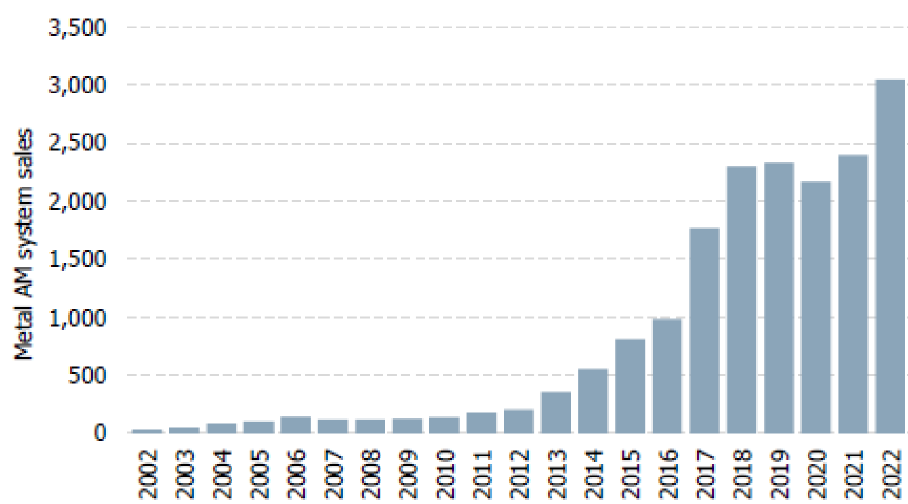
The ASP declined from 2001 through 2010, as shown in the previous graph. The ASP rose sharply after 2010. One reason for the increase was a gaining of traction of high-end AM machines, including metal systems, which can be up to 10 times the price of an average polymer system. Another reason is that sales of machines at the low end of the industrial system segment ($10,000—$30,000) began to decline due to the growth and popularity of desktop 3D printers. Together, these factors caused the ASP of industrial systems to increase.

Since 2017, the ASP of industrial AM systems has stabilized at between $95,000 and $100,000. Over the past two years, the ASP declined, likely due to an increase in companies purchasing systems in the $10,000–50,000 range.

Metal AM systems

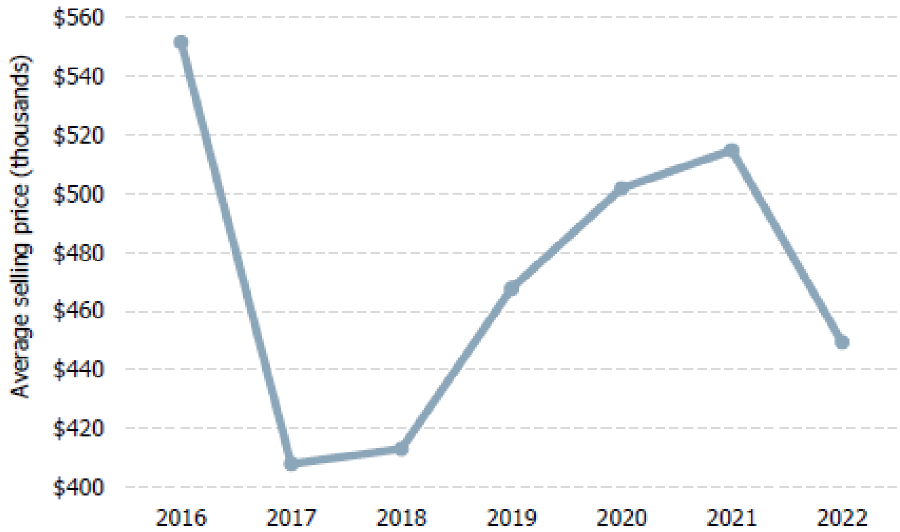
Sales of AM systems for metal parts increased by 27.2% in 2022. Wohlers Associates has been tracking this market segment for 20 years, as shown in the following graph. An estimated 3,049 metal AM machines were sold in 2022, compared to the 2,397 sold in 2021.

Fig. 148. Metal AM systems growth; source: Wohlers Associates



An estimated $1.370 billion in revenue was produced from sales of metal AM machines in 2022. The ASP of a metal AM machine was $449,413 in 2022, compared to $514,823 in 2021, $501,844 in 2020, and $467,635 in 2019. The following graph reflects these ASPs (in thousands of dollars).

Fig. 149. Average selling price of metal industrial AM systems; source: Wohlers Associates



Desktop 3D printers

Wohlers Associates defines desktop 3D printers as AM systems that sell for less than $5,000. This category includes RepRap-derivative material extrusion (MEX) products such as those from Cubicon, Prusa, Tiertime, XYZprinting, and Zaxe. Desktop vat photopolymerization (VPP) systems are also growing in prominence for prototyping, education, and final part production in applications such as dentistry.

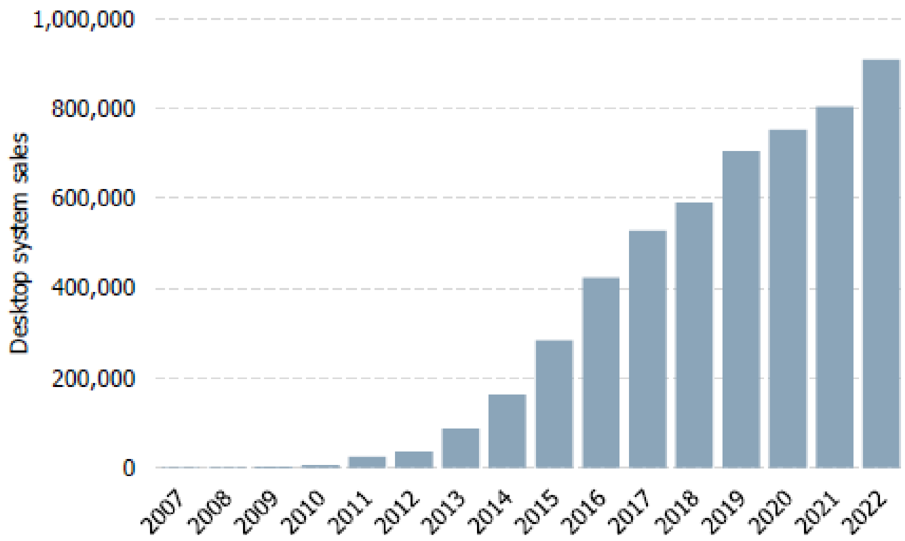
Sales of desktop 3D printers are non-traditional and difficult to track. Countless small companies around the world, including many startups, produce, sell, and distribute these products. Many parts, kits, and subassemblies are available on Amazon, eBay, and other online marketplaces.

Many companies, such as Formlabs, MakerBot, and Ultimaker, previously sold desktop printers only and now also sell products priced above $5,000. Meanwhile, some systems priced less than $5,000 offer relatively large build volumes, fine part quality, and good machine reliability. Many industrial systems are priced at 10 times more than desktop printers, but that does not mean they are 10 times better. Many desktop printers are being used productively for concept modeling, prototyping, and even some final part production.

Sales growth

Collectively, desktop systems have experienced astounding development since 2012, as shown in the following graph. Sales growth was 6.1% in 2022, representing total revenue of an estimated $1.022 billion. This figure was calculated using sales from six system manufacturers. Growth was 7.0% in 2021, 6.7% in 2020 and 19.4% in 2019. The following graph represents the estimated unit sales each year.

Fig. 150. Desktop systems sales; source: Wohlers Associates



The market for under-$500 3D printers is believed to have grown significantly over the past few years. Hundreds of products priced in the $150–500 range can be found online. Many of them are produced in regions of the world where product development and manufacturing costs are low.

Because of the way the under-$500 products are sold, it is challenging to estimate unit sales. Even the people that work within this market segment are unsure and admit that the available information offers rough estimates, at best.

Materials and R&D

Most manufacturers of desktop 3D printers report that polylactic acid (PLA) is the material making the most money. Survey results show that twice as many respondents reported that PLA produced the most money compared to acrylonitrile butadiene styrene (ABS).

The primary focus of R&D for desktop printer manufacturers in 2022 was on new materials development and larger and faster systems. ZYYX released the ZYYX Pro II MEX system with a build volume of 285 x 235 x 210 mm (11.2 x 9.6 x 8.3 in). Prusa of the Czech Republic released the Prusa XL and SL1S Speed, large MEX and VPP systems, respectively. The company also released a filament made from 100% recycled PLA.

To scale into production using desktop systems, companies are doing R&D to increase reliability and create an efficient and reliable workflow. Prusa offers an automated print farm called the Prusa Pro AFS which includes 34 Original Prusa 3D printers that run autonomously. A print farm of more than 600 printers is running at the company's headquarters in Prague.

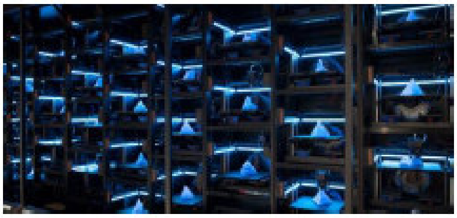


Fig. 151. Print farm of desktop 3D printers, courtesy of Prusa

AM material sales

In 2022, $3.26 billion was spent globally on materials for all AM industrial and desktop AM systems. This represents an increase of 25.5% over the $2.598 billion generated in 2021. These dollar figures include sales of powders, liquid photopolymers, pellets, filaments, wires, sheet materials, and all other materials used for AM.

Year	Sales	Year	Sales
2001	$71.0	2012	$417.0
2002	$81.2	2013	$493.9
2003	$93.4	2014	$640.0
2004	$128.9	2015	$768.3
2005	$151.0	2016	$903.0
2006	$189.5	2017	$1,133.7
2007	$220.9	2018	$1,494.7
2008	$238.0	2019	$1,916.1
2009	$217.8	2020	$2,105.2
2010	$265.9	2021	$2,598.2
2011	$327.1	2022	$3,259.5

The following graph and table provide a 22-year history of global material sales for AM systems.

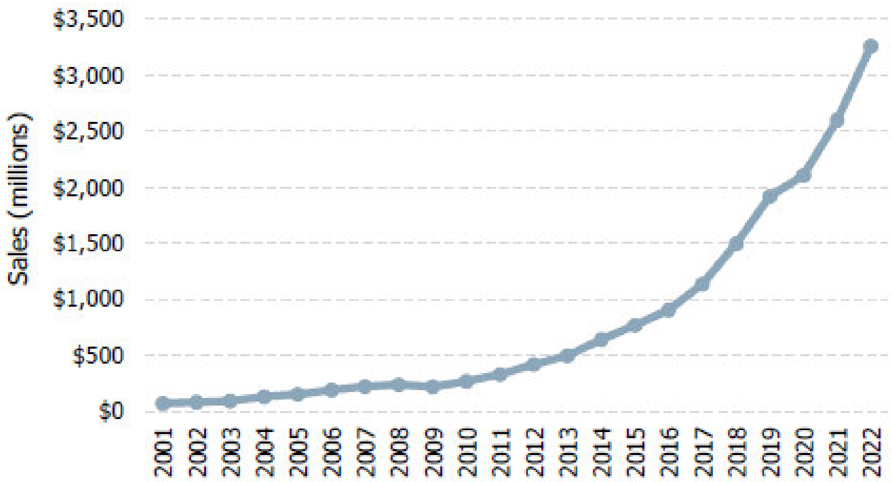


Fig. 152. Global material sales for AM systems; source: Wohlers Associates

The following chart shows the $3.26 billion materials market segmented by material type. In 2022, for the second consecutive year, polymer powders exceeded the photopolymers segment. Historically, the photopolymer segment has been the largest, due in part to its popularity for prototyping and other applications. PBF is believed to be the most popular process for final part production, so the recent growth in powders points to the strong adoption of AM for production applications.

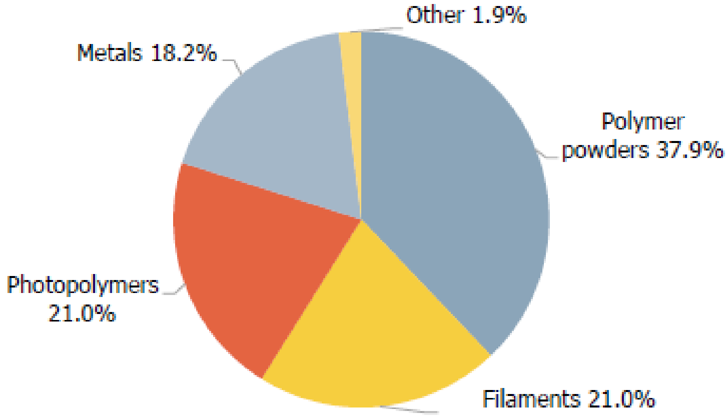


Fig. 153. Materials market segmented by type; source: Wohlers Associates

In 2022, photopolymers and polymer filaments were equal in market share. Metal has been available for about half of the industry's 35-year history and represented 18.2% of total materials revenue in 2022. The "Other" segment includes ceramics, waxes, and materials for binder jetting (BJT) and sheet lamination (SHL).

For three decades, photopolymer was the dominant AM material. Over the past three years, as seen in the following chart, polymer for PBF (red) overtook photopolymer (gray). The values in the vertical axis represent millions of dollars in revenue from these materials. Wohlers Associates expects polymer powders to continue to outpace photopolymers as the dominant AM polymer material over the coming years as series production applications increase.

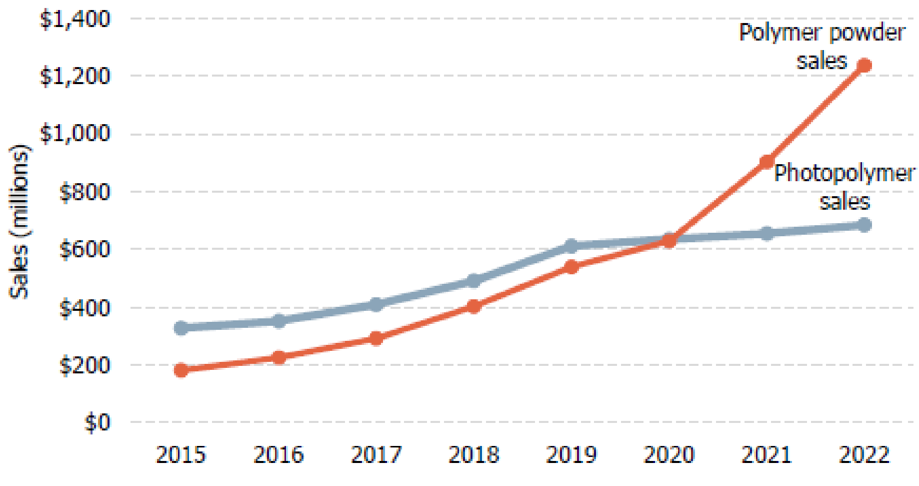


Fig. 154. Photopolymer versus polymer powder sales; source: Wohlers Associates

Photopolymers

An estimated $684.4 million was spent on photopolymers in 2022. This is an increase of 4.6% from 2021. The following graph and table provide a 21-year history of photopolymer sales for AM systems worldwide. The estimates shown are in millions of dollars.

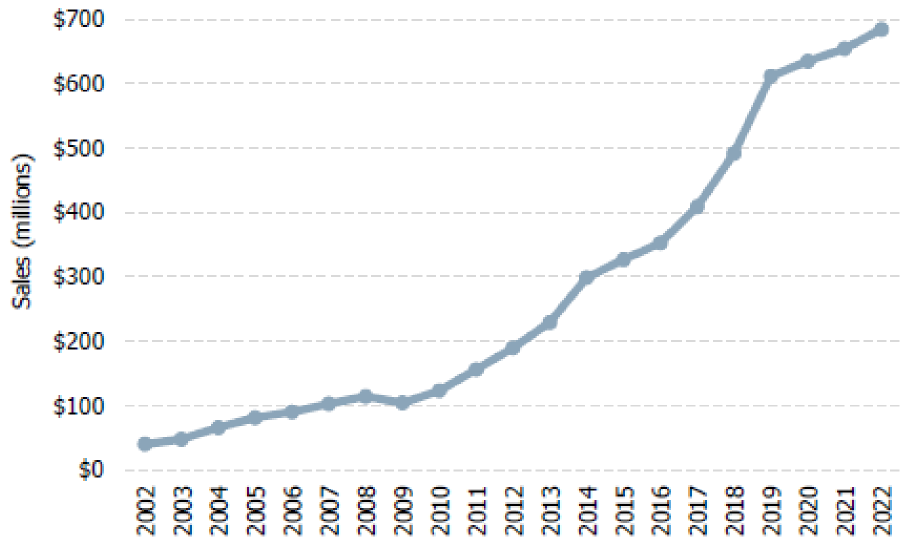


Fig. 155. Growth in photopolymer sales; source: Wohlers Associates

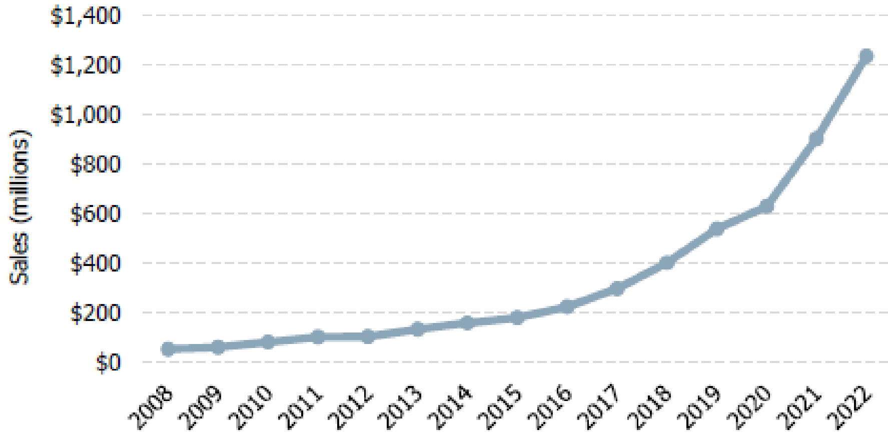
Year	Sales	Year	Sales
2002	$39.4	2013	$228.9
2003	$47.3	2014	$298.4
2004	$65.6	2015	$326.6
2005	$80.7	2016	$352.2
2006	$89.6	2017	$408.5
2007	$102.5	2018	$491.5
2008	$114.0	2019	$611.4
2009	$103.7	2020	$634.9
2010	$122.8	2021	$654.2
2011	$155.8	2022	$684.4
2012	$189.0		

Source: Wohlers Associates

Polymer powders

Worldwide consumption of thermoplastic polymers for PBF systems grew to $1.236 billion in 2022, up 37.0% from 2021. This includes powders for laser PBF and materials for multi jet fusion (MJF) systems from HP.

Fig. 156. Growth in polymer powder sales; source: Wohlers Associates



Year	Sales	Year	Sales
2008	$55.0	2016	$225.8
2009	$62.0	2017	$291.5
2010	$83.0	2018	$402.1
2011	$104.0	2019	$539.1
2012	$105.0	2020	$629.2
2013	$135.0	2021	$902.0
2014	$160.0	2022	$1,235.5
2015	$181.0		

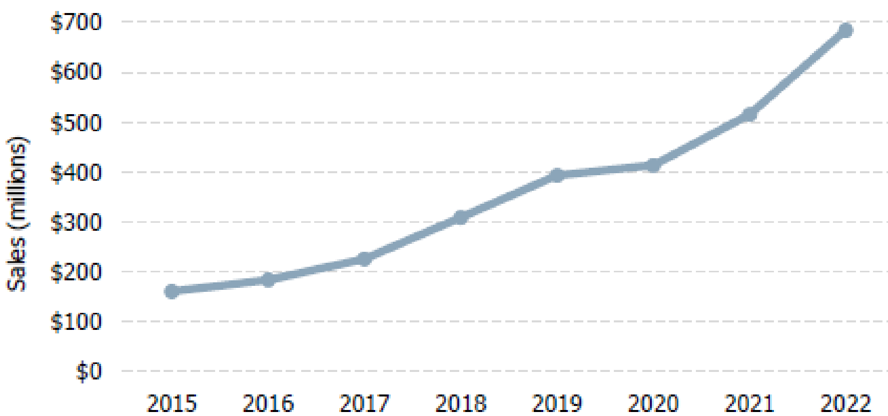
Source: Wohlers Associates

Filaments

In recent years, hundreds of companies have developed and commercialized desktop MEX 3D printers. This has sparked new commercial development of filaments. Most desktop printers are "open," meaning that they accept third-party materials. Most of these filaments are sold at competitive prices.

Wohlers Associates estimates that thermoplastic filament sales grew by 32.8% to $684.9 million in 2022, as shown in the following graph and table. This compares to $515.9 in 2021.

Fig. 157. Growth in filament sales; source: Wohlers Associates



Year	Sales	Year	Sales
2015	$160.6	2019	$394.3
2016	$184.2	2020	$414.1
2017	$225.7	2021	$515.9
2018	$308.6	2022	$684.9

Source: Wohlers Associates

Metals

Revenue from metals for AM grew 25.1% in 2022 to an estimated $592.5 million, up from $473.6 in 2021. Wohlers Associates began to track the sales of metals for AM in 2009, as shown in the following graph and table. Metals used for AM are primarily powders, but also include wires, filaments, sheets, and tapes.

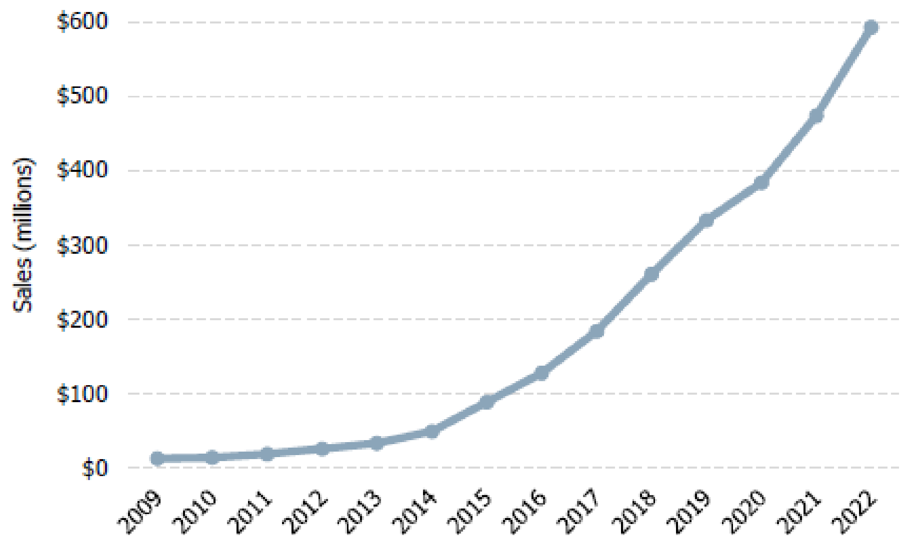


Fig. 158. Growth in metal sales; source: Wohlers Associates

Year	Sales	Year	Sales
2009	$12.0	2016	$126.8
2010	$13.5	2017	$183.4
2011	$18.0	2018	$260.2
2012	$24.9	2019	$332.7
2013	$32.6	2020	$383.4
2014	$48.7	2021	$473.6
2015	$88.1	2022	$592.5

Source: Wohlers Associates

Service providers

AM service providers are companies that produce parts and offer other services on a contract basis to a wide range of organizations. In recent years, the scope of services for parts has grown. It includes conventional service bureaus that have been in business since the early 1990s. It also includes AM marketplaces and communities such as Sculpteo, Shapeways, Xometry, and independent 3D print shops.

A service provider may be a single individual with a desktop 3D printer selling parts locally. At the other end of the spectrum are "mega" service providers with more than 100 industrial machines installed at several locations worldwide. Companies within this category may refer to themselves as service providers, job shops, or contract manufacturers.

Primary service market

Independent service providers worldwide generated an estimated $7.508 billion from the sale of parts produced by AM systems in 2022. This is up 20.4% from the $6.235 billion in 2021. This revenue excludes sales generated by service provider businesses within companies such as Stratasys. The $7.508 billion represents nearly 69.9% of total AM services in 2022, which reached $10.738 billion. These additional services include system maintenance contracts, training, seminars, conferences, expositions, advertising, publications, contract research, and consulting services.

The following graph shows service provider revenue estimates (in millions of dollars) for the past 29 years. The bars represent primary revenue only—money from parts produced on AM equipment. The graph excludes revenue from secondary processes, such as tooling (not produced on AM equipment), parts made from this tooling, castings, and machined parts from computer numerical control (CNC) processes. Also, they exclude design, engineering, and other services.

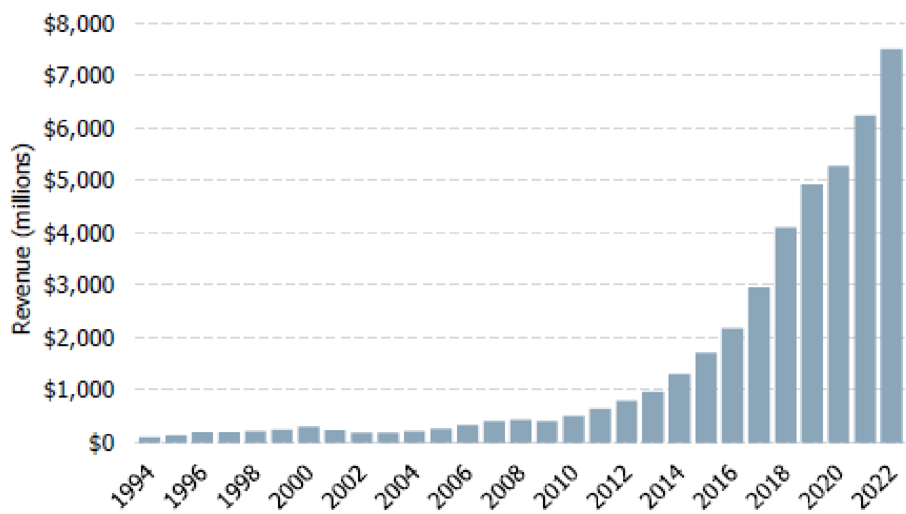


Fig. 159. Service provider revenue growth; source: Wohlers Associates

Service provider survey

Since 2004, Wohlers Associates has collected input from service providers to help determine the state of the industry. Most respondents are "traditional" service providers as defined previously. However, several online marketplaces also contribute.

For this year's report, 119 companies in 31 countries participated in a formal survey. Of the participating companies, 39 are from the U.S., 10 from Germany, 10 from the UK, six each from India and Switzerland, five from Italy, and four from Sweden. Three each are from Canada, Finland, South Africa, and Turkey. Two each are from Australia, Belgium, the Czech Republic, Denmark, the Netherlands, New Zealand, and the UAE. One each is from Argentina, Cyprus, Greece, Hungary, Israel, Japan, Malaysia, the Philippines, Portugal, Saudi Arabia, Singapore, Spain, and Thailand.

Companies are invited to participate in the survey on a voluntary basis. It is believed that companies doing well are more likely to respond than those who had a poor year. Those who respond change slightly each year. Some companies are acquired, go out of business, or stop responding, while startups and other companies participate in the survey for the first time. Many companies, thankfully, respond year after year.

Contributing service providers

The following table lists 119 service providers from around the world that generously contributed information and data for this report.

Company	Country	Website
+90	Turkey	www.arti90.com
3D Formtech	Finland	www.3dformtech.fi
3D Makers Zone	Netherlands	www.3dmakerszone.com
3D MetPrint AB	Sweden	www.3dmetprint.com
3D Musketeers	U.S.	www.3dmusketeers.com
3D Product Development	India	www.3dpd.net
3DChimera	U.S.	www.3dchimera.com
3DEO, Inc.	U.S.	www.3deo.co
3Dit Corp.	Saudi Arabia	www.3dit.net
3DnA	Italy	www.3dnasrl.it
3Faktur GmbH	Germany	www.3faktur.com
4C Engineering	Turkey	www.4c.com.tr
Additive at Scale	U.S.	www.addema.se
Additive Engineering Solutions	U.S.	www.additiveeng.com
Additure	UK	www.additure.co.uk
ADDMAN Group	U.S.	www.addmangroup.com
AdvancedTek	U.S.	www.advancedtek.com
Agile Manufacturing	Canada	www.aps3d.com

Company	Country	Website
Alumina Systems GmbH	Germany	www.agile-manufacturing.com
American Additive Manufacturing	U.S.	www.americanadditive.com
AML3D Limited	Australia	www.amltec.com
AM-Rauch GmbH&CoKG	Germany	www.am-rauch.com
Anima	Greece	www.anima.gr
AnyShape	Belgium	www.any-shape.com
aran r&d	Israel	www.aran-rd.com
ARCH Additive	U.S.	www.arch-medical.com
Aristo-Cast Inc	U.S.	www.aristo-cast.com
ArpTech	Australia	www.arptech.com.au
ARRK Europe	UK	www.arrkeurope.com
Bastech, Inc.	U.S.	www.bastech.com
BERMARK DESIGN LTD	Thailand	www.bermark.com
CA Models Ltd	UK	www.camodels.co.uk
Caracol	Italy	www.caracol-am.com
Castheon Inc	U.S.	www.castheon.com
CIDEAS Inc	U.S.	www.buildparts.com
cirp GmbH	Germany	www.cirp.de
Creabis GmbH	Germany	www.creabis.de
Creatz3D Pte Ltd	Singapore	www.creatz3d.com.sg
CRP Technology S.r.l.	Italy	www.crp-group.com
CRPM at Central University of Technology	South Africa	www.cut.ac.za/crpm
CURRANT 3D	U.S.	www.currant3d.com
Custom Prototypes Inc.	Canada	www.customprototypes.com
DAVINCI 3D A/S	Denmark	www.davinci.dk
DELRAY Systems LLC	U.S.	www.3d-printer.com
Delva Oy	Finland	www.delva.fi
Dependable Pattern Works	U.S.	www.dpwcorp.com
Digital Manufacturing Centre	UK	www.digitalmanufacturingcentre.com
Digital Mechanics AB	Sweden	www.digitalmechanics.se
Dinsmore, Inc.	U.S.	www.dinsmoreinc.com
DT2 NEW CONCEPT	Portugal	www.dt2rmc.pt
EBK Hungary Kft	Hungary	www.ebkhungary.com
ECOPARTS AG	Switzerland	www.ecoparts.ch
Exentis Group AG	Switzerland	www.exentis-group.com
Fabric8Labs	U.S.	www.fabric8labs.com
Falcon Technologies International	UAE	www.falconrak.com
Fi Innovations	New Zealand	www.f-i.co.nz
Fiberneering	Netherlands	www.fiberneering.com

Company	Country	Website
Fission 3D	Cyprus	www.fission3d.com
FIT AG	Germany	www.pro-fit.de
Fixie Ltd.	UK	www.fixie3d.com/
GF Casting Solutions	Switzerland	www.gfcs.com
Graphite Additive Manufacturing	UK	www.graphite-am.co.uk
HiETA Technologies	UK	www.hieta.co.uk
Humtown Additive	U.S.	www.humtown.com
Ineo prototipos SL	Spain	www.ineo.es
Innomia	Czech Republic	www.innomia.cz
Lasertech	Sweden	www.lasertech.se
LGM	U.S.	www.lgm3d.com
Makelab	U.S.	www.makelab.com
Marco Polo Products Pvt Ltd	India	www.marcopolo.co.in
Materialise	Belgium	www.materialise.com
Mentis 3D	South Africa	www.mentis3d.co.za
Metal Heart	South Africa	www.metalheart.co.za
Met-L-Flo, Inc.	U.S.	www.metlflo.com
Michael Sander Kunststofftechnik GmbH	Germany	www.sander-kunststofftechnik.de
Midwest Prototyping	U.S.	www.midwestproto.com
MT Aerospace AG	Germany	www.mt-aerospace.de
My3D Concepts Corp.	Philippines	www.my3dconcepts.com
Objectify Technologies Pvt Ltd	India	www.myobjectify.com
Oerlikon AM	Switzerland	www.oerlikon.com
Oerlikon AM US Inc.	U.S.	www.oerlikon.com
officina ciesse	Italy	www.ci-esse.eu
OFFICINA CI-ESSE SRL	Italy	www.ci-esse.it
Ogle Models & Prototypes	UK	www.oglemodels.com
Paarts Additive, s.r.o.	Czech Republic	www.paarts.com
PADT, Inc.	U.S.	www.padtinc.com
Pebble3D Sdn Bhd	Malaysia	www.pebblereka.com
PLG Global Limited	UK	www.plgglobal.co.uk
PLG Group	Turkey	www.poligonmuhendislik.com
PrinterPrezz (DBA Vertex Manufacturing)	U.S.	www.printerprezz.com
ProtoCAM	U.S.	www.protocam.com
ProtoShape 3D-Printing AG	Switzerland	www.protoshape.ch
protosys technologies pvt ltd	India	www.protosystech.com
PROTOTAL Damvig A/S	Denmark	www.prototal.se
Prototal Industries AB	Sweden	www.prototal.se

Company	Country	Website
Quickparts	U.S.	www.quickparts.com
RAM3D	New Zealand	www.ram3d.co.nz
Rapid Prototype and Manufacturing LLC	U.S.	www.rpplusm.com
Rapid Prototyping Services, llc	U.S.	www.rapidps.com
RapidMade, Inc.	U.S.	www.rapidmade.com
Realize, Inc.	U.S.	www.realizeinc.com
Robert Hofmann GmbH	Germany	www.hofmann-imm.de
Salon Metalelektro	Finland	www.smegroup.fi
Schubert Additive Solutions	Germany	www.schubert.group
SICAM Corporation	U.S.	www.sicam.com
Solaxis Ingenious Manufacturing Inc	Canada	www.solaxis.ca
Solidiform Inc.	U.S.	www.solidiform.com
SOLIZE Corp.	Japan	www.solize.com
Spectroplast AG	Switzerland	www.spectroplast.com
Speedpart GmbH	Germany	www.speedpart.de
Stratnel Technologies LLP	India	www.stratnel.com
Synergeering Group LLC	U.S.	www.synergeering.com
TAMVINCI 3D Construct LLC	UAE	www.tamvinci.com
The 3D Printing Store	U.S.	www.the3dprintingstore.com
The Technology House	U.S.	www.tth.com
Trideo	Argentina	www.trideo3d.com
TriMech Solutions	U.S.	www.trimech.com
United Performance Metals	U.S.	www.upmet.com
Wipro 3D	India	www.wipro-3d.com

Source: Wohlers Associates

Survey results

An estimated total of 1,767 industrial AM systems are installed at the 119 companies that responded to the service provider survey. In 2022, independent service providers reported overall business growth of 20.4%.

The technology with the highest number of installed systems among the survey respondents was stereolithography (SLA) from 3D Systems, a VPP process. According to the survey results, 317 SLA systems were operating at these companies in 2022. For the third consecutive year, the combined number of polymer PBF systems from 3D Systems, EOS, and HP exceeded the number of SLA systems, with a total of 368 machines. Of the 1,767 systems installed at the companies that responded to the survey, 554 systems are from less-established system manufacturers. This may indicate a trend away from the big system manufacturers that dominated the industry for much of its first three decades.

Polymer PBF from EOS is the second most popular technology, with 187 machines installed among the service providers that responded. MEX from Stratasys is the third most popular, with 153 units in operation. The most popular metal AM technology is from EOS, with 100 installed systems, followed by Concept Laser from GE Additive, with 44 systems operating across the respondents.

In 2022, 53.4% of the service provider respondents manufactured polymer parts only, up from 51.3% in 2021. The survey showed that 17.8% of companies are producing metal AM parts only, up from 11.3% in 2021. The remaining 28.7% produce both metal and polymer parts, down from 37.4% in 2021.

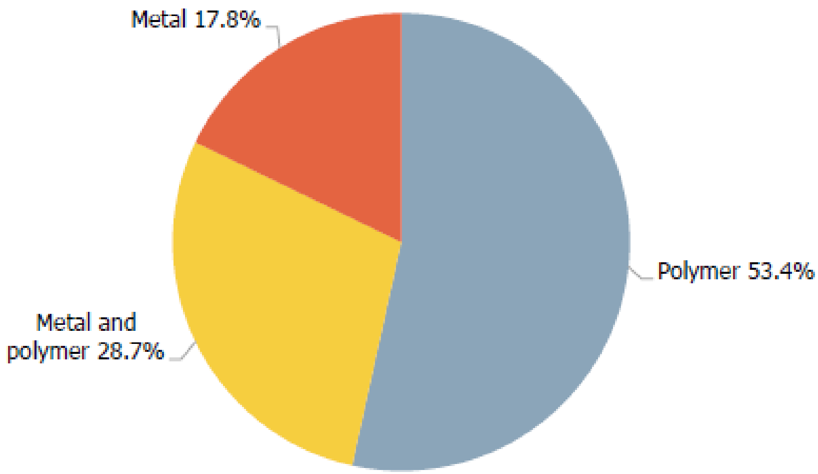


Fig. 160. Material type used by service providers; source: Wohlers Associates

Pre- and post-processing

In recent years, the AM industry has become more aware of the need for design for additive manufacturing (DfAM). One of the key reasons is to reduce the time and expense of pre- and post-processing of parts. Service providers were asked what proportion of their part costs are attributed to pre-processing (i.e., model repair, build orientation, part nesting, build preparation, etc.), printing (i.e., actual building of the parts), and post-processing (i.e., support material removal, cleaning, surface treatment, etc.). The results were divided among service providers that produce metal AM only, polymer AM only, and both. The following table shows the results for 2022.

	Metal	Polymer	Both
Pre-processing	9.9%	11.6%	11.8%
Printing	60.0%	66.2%	58.6%
Post-processing	30.1%	22.2%	29.5%

Source: Wohlers Associates

The following chart shows the proportional costs of printing (gray), post-processing (red), and pre-processing (yellow) for metals since 2017. The figures show that post-processing costs are slowly increasing.

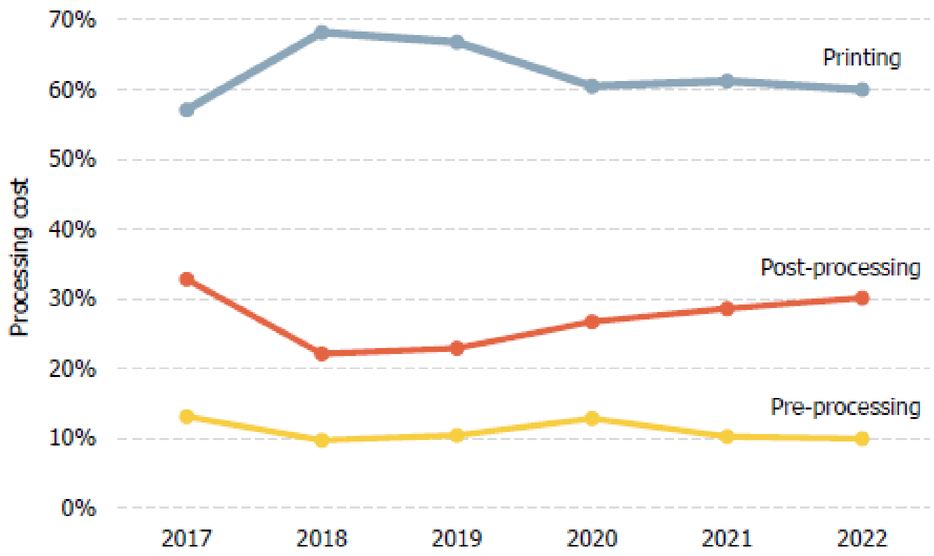


Fig. 161. Metal part costs; source: Wohlers Associates

The following graph shows the proportional costs for printing (gray), post-processing (red), and pre-processing (yellow) for polymers since 2017. The slight decrease in post-processing can potentially be linked to the use of more automated polymer post-processing technologies that have come to market in the past few years.

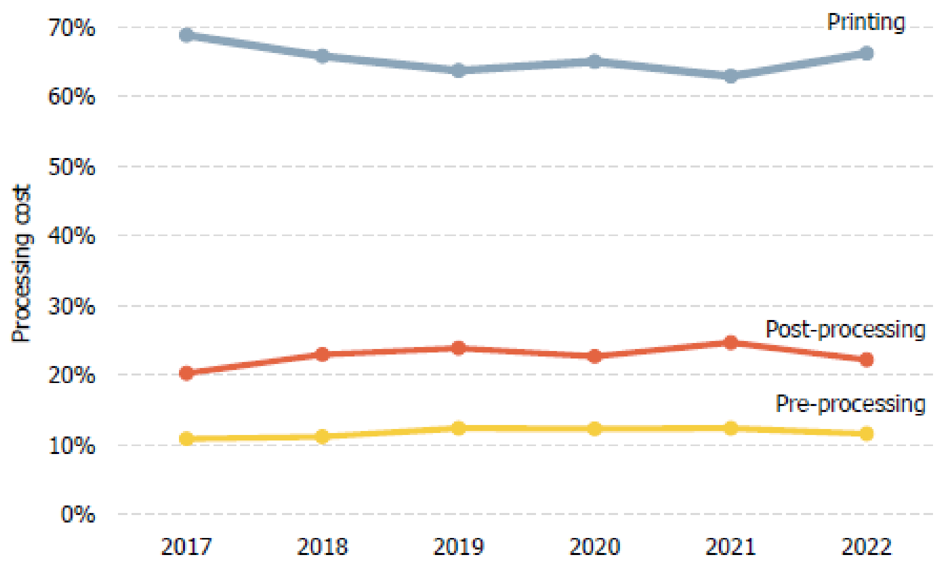


Fig. 162. Polymer part costs; source: Wohlers Associates

Most profitable AM processes

Service providers were asked which AM process was most profitable in 2023. At 11.4%, polymer PBF from HP and metal PBF from EOS were the top choices, as shown in the following chart. Polymer PBF from EOS was second, followed by MEX from Stratasys.

The "Other" category shows that 39.5% of the survey respondents said their most profitable AM process is from less-established system manufacturers. This supports a gradual broadening of the market for system manufacturers and a move away from the big players that have dominated the industry in the past.

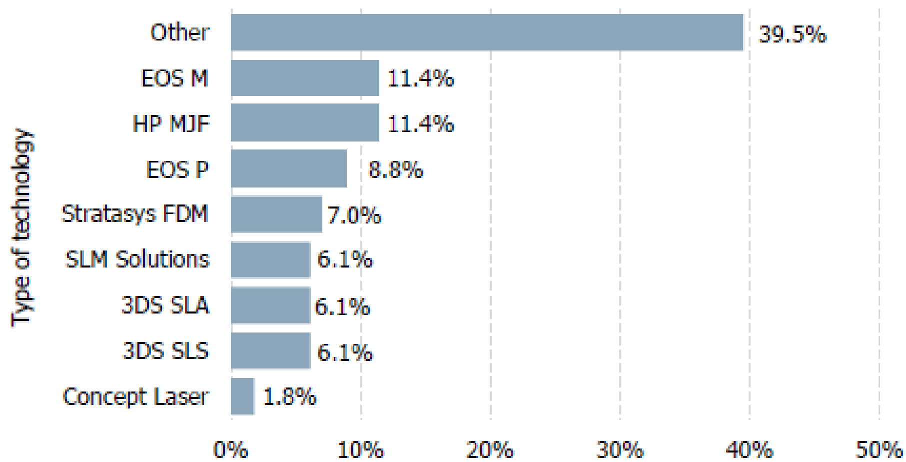


Fig. 163. Most profitable AM processes; source: Wohlers Associates

Those surveyed were asked which technology they would most likely purchase if they were going to expand their AM capacity. The most popular response was MJF from HP, as shown in the following chart. The second was metal PBF from EOS, and the third most popular was polymer PBF from EOS. The responses to this question show increasing interest in PBF systems. The products in "Other" are from 3D Systems (PBF, VPP, and MJT) and metal PBF systems from Desktop Metal, DMG Mori, ExOne, GE Additive (Arcam) or are products from less-established manufacturers.

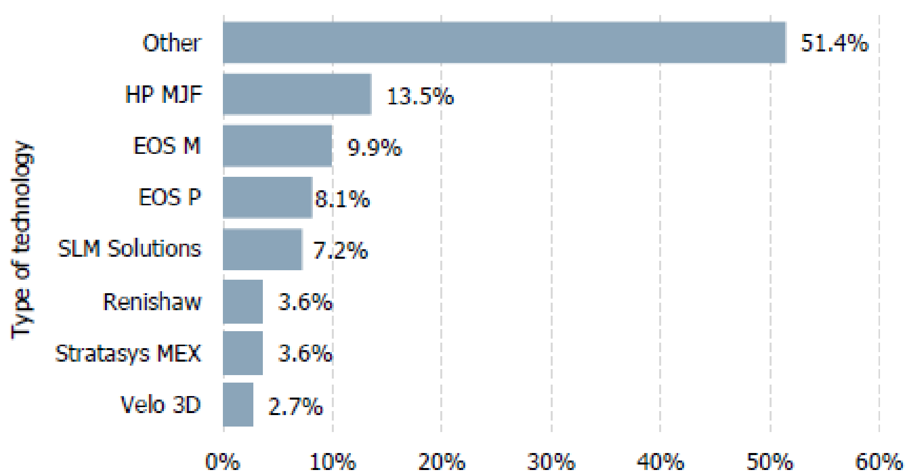
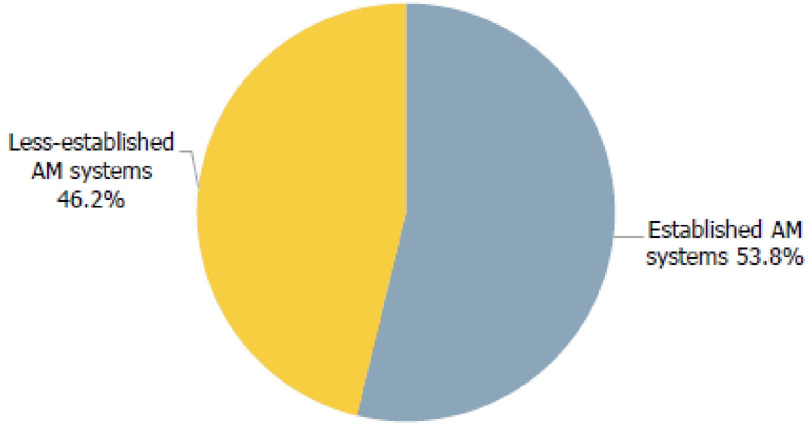


Fig. 164. AM systems service providers are most likely to acquire; source: Wohlers Associates

Service providers have traditionally purchased systems from established AM manufacturers such as 3D Systems, EOS, and Stratasys. However, in 2022, service providers that responded to the survey added 156 less-established AM systems (53.8%) out of a total of 290 machines purchased.

Fig. 165. Well-established systems versus less-established systems; source: Wohlers Associates



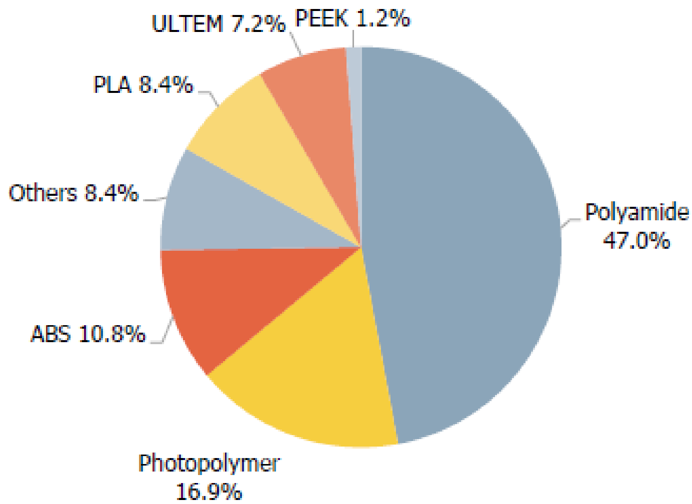
This is the third consecutive year that more machines have been purchased from less-established companies. It shows a possible trend toward young companies that are successful in competing with more developed manufacturers.

Most profitable materials

Service providers were asked which material is making the most money for their companies. The following two charts show the most profitable polymers and metals.

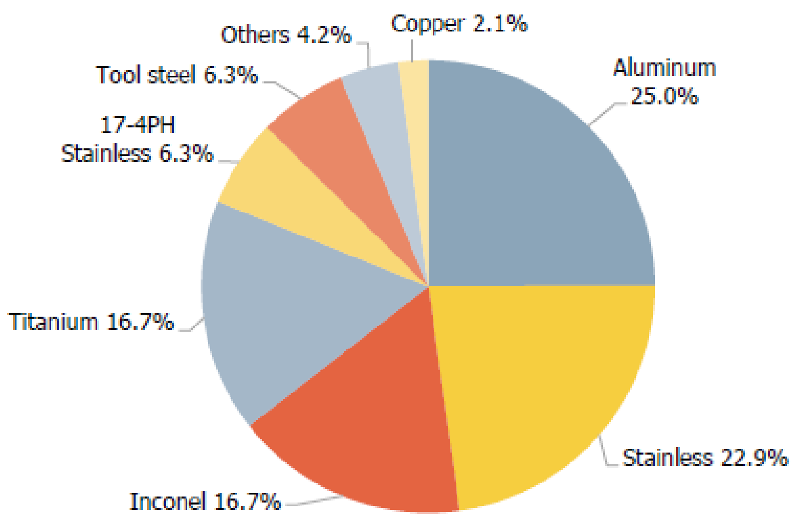
Polyamide (PA), a thermoplastic also known as nylon, is the most profitable polymer according to the survey respondents, as shown in the following chart. In 2022, 47.0% of respondents said PA was the most profitable material, down from 48.9% from 2021 and 62.2% in 2020.

Fig. 166. Most profitable polymer materials; source: Wohlers Associates



The following chart shows the percentage of metals that companies reported as the most profitable. Aluminum ranks at the top, according to the respondents, with 25.0% of the total. In 2021, aluminum was also the most profitable according to 22.0% of companies. Inconel decreased from 19.5% in 2021 to 16.7% in 2022. Meanwhile, 17-4PH stainless steel decreased from 17.1% to 6.3% over the same period. Titanium's share increased from 12.2% to 16.7%.

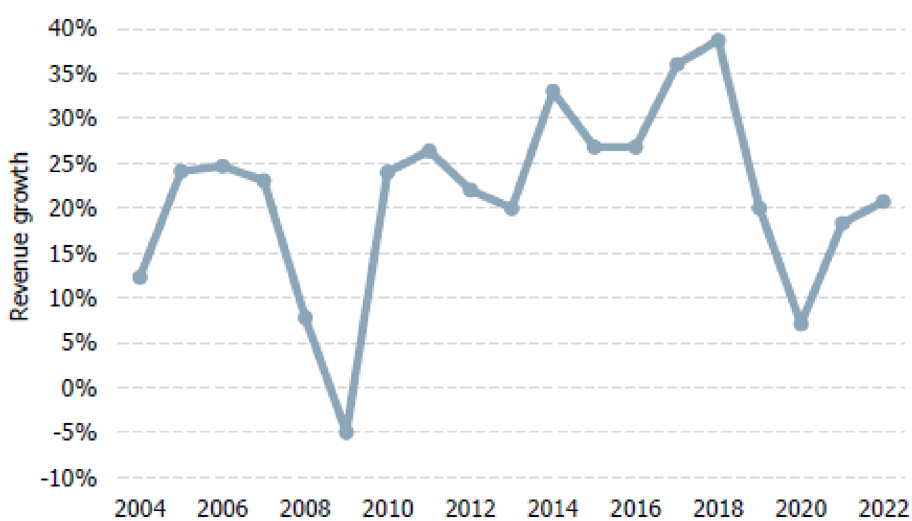
Fig. 167. Most profitable metals; source: Wohlers Associates



Revenue growth

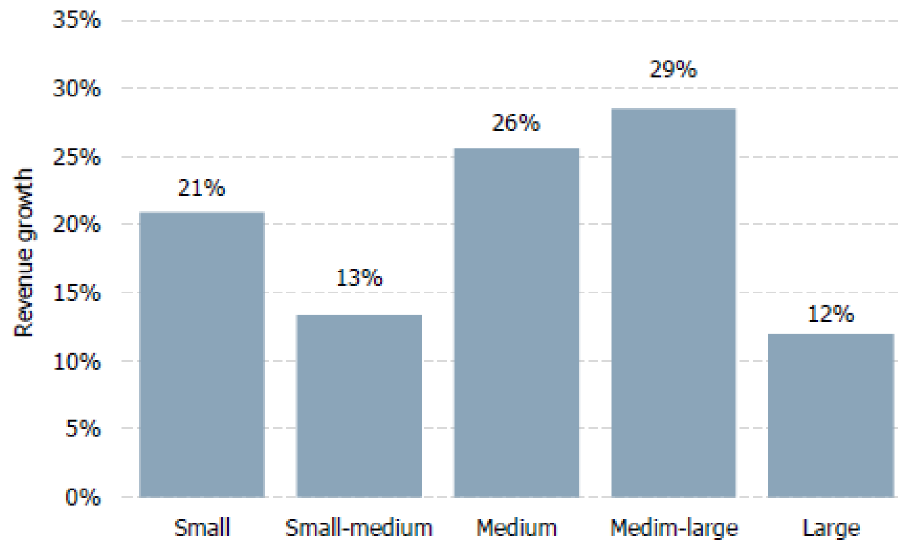
The following graph shows the average rate of growth in service provider revenues from primary services over the past 18 years. Primary services consist of revenues from parts produced directly on AM systems. In 2022, the average growth rate increased to 20.4% from 18.3% in 2021 and 7.1% in 2020.

Fig. 168. Average service provider revenue growth; source: Wohlers Associates



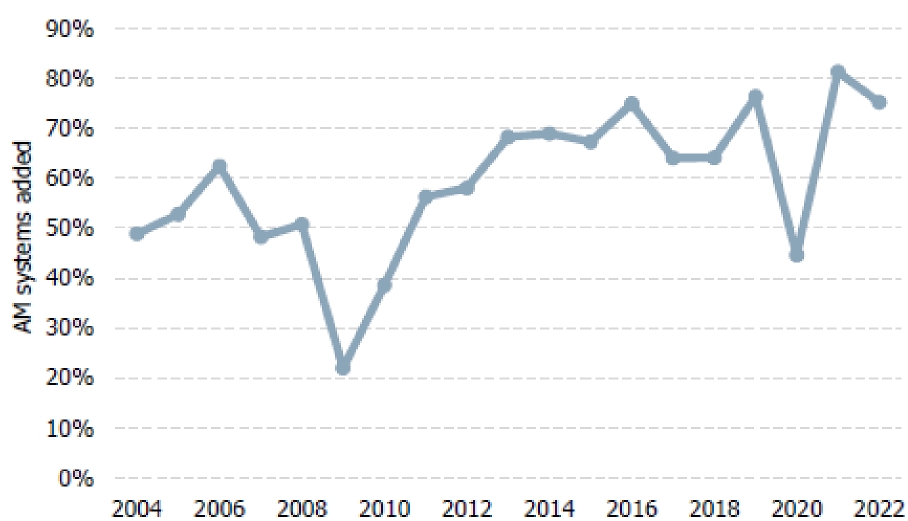
The following chart shows the revenue growth segmented by small (0–20 employees), small-medium (21–50 employees), medium (51–100 employees), medium-large (101–250 employees), and large companies (251+ employees). Medium-large-sized company revenue grew the most in 2022, compared to others.

Fig. 169. Service provider revenue growth by company size; source: Wohlers Associates



The following graph shows the percentage of respondents that added AM systems to their operations. In 2022, 75.2% of service providers added new machines to their capacity. This is a slight decrease over 2021 when 81.4% of these companies added machines. In 2020, 44.6% added new machines and in 2019, 76.4% added new machines. The low rate of machines purchased in 2020 was likely associated with the pandemic, which affected the entire industry.

Fig. 170. Growth of respondents that added AM systems; source: Wohlers Associates



Comments from service providers

Service providers were invited to share comments on their businesses. The following anonymous remarks were found to be interesting and insightful. The comments were edited for spelling, grammar, and clarity, but every attempt was made to preserve their meaning and intent. All comments were provided in early 2023.

"Continued growth in 2022; slightly tempered expectation for 2023, but we see plenty of opportunity to grow."

"We experienced decreasing use of 3D-printed metal parts within the overall manufacturing industry. The tooling industry has not yet adopted metal 3D printing as an accepted/preferable process."

"Huge growth in the energy sector. Aerospace is now coming back after the pandemic."

"The market remains very tight and competitive. However, the past year has been positive for growth, and we expect this to continue. We have seen two of our nearest competitors struggle in the market and have reduced operations. The market is much more challenging than some suggest."

"In 2022, our company aimed to boost AM with a wider service palette and some research in new technologies. Despite COVID and an economic crisis, we are moving ahead and aim to targets."

"I expect some of the producers of materials will greatly reduce their activity or disappear because they now understand the specialization and fragmentation of the market."

"Nearly all existing orders for final parts for the second half of 2022 were delayed into 2023. That is why end-use part production declined in 2022. This is a direct effect of the difficult economic situation in Europe."

"Our part services department is steadily growing in pre- and post-processing capabilities."

"We are in the process of growing into a bigger space, adding personnel, AM systems, and expanding our services."

"We would like to add a big MEX machine and polymer PBF with open software and high-temperature chamber (like Farsoon HT)."

"After 10 or more years in the metal AM business, we believe from our vantage point and pipeline that 2023 will finally be the breakout year we have all aspired to have!"

"Business started very well but slowed down in the second half of 2022. We are trying to get more into highly integrated industrial manufacturing using AM as part of the complete process."

"We added another EOS M 290 machine and are partnering with several spinal and orthopaedic manufacturers to increase production. In 2022, we broke through the milestone of assisting 1,000 patients and the manufacture of 10,000 3D-printed spinal cages."

"Prototyping and small batch runs are turning into serial production."

"We grew a lot in revenue by exporting to Europe."

"We grew our technology offering significantly this year through the Stratasys acquisitions in powder bed fusion (SAF), digital light processing (DLP), and VPP technologies. We have greatly expanded our offering and focus on end-use production applications. The year was a big learning curve for us, but it positions us well for the future to address customer needs in additive production."

"We have an increased focus on military/defence applications and onsite equipment in the field."

"Company performance was partially influenced by COVID and an energy crisis last year."

"The metal AM business has shown the best growth in 2022."

"While we have added a larger format VPP machine this year, our focus is more on the production environment of AM. We will probably always hang on to prototyping business. Our long-term vision is on the production aspect of AM in both plastics and metals."

"Consider vacuum casting in your report—a technology that has been marinated and condemned to death for years, but continues to be an essential piece in small-series production. It complements additive technologies."

"We are growing each year. Visit us to understand why."

"Materials for end-use applications are valuable."

"We are working through our journey on implementing automation and software improvements. Meanwhile, we are starting to enjoy the benefits in a very tight labor market. We now produce far more with fewer people than before, which is putting us in a good position."

"Key development programs are now moving into production in 2023. We see significant growth in 2024 and beyond."

"We hope to increase the production capacity for polymer PBF and promote the market for large parts."

"We have added design and engineering to our AS9100 scope and have invested in laser scanning to support internal metrology and external reverse engineering and design services."

"Looking for metal 3D printing, especially for tooling applications."

"We made significant strides this year converting more customers to AM for production parts. Supply chain constraints, along with fully validated systems in Carbon DLS and HP MJF for medical purposes, have demonstrated the important role AM plays in the manufacturing supply chain to our customers. Improved material performance and post-processing systems within the industry have also helped propel the industry to the next stage of growth."

"We provide AM services primarily in concrete. We have seen an exponential increase in demand for 3D-printed buildings and structures. We partnered with Twente AM to provide leading-edge robotic 3D printing solutions. We also work closely with concrete mix providers, such as Sika, to develop concrete mixes for 3D printing."

"We added a secondary vapor smoothing technology for finishing MJF parts. Also, more customers are starting to migrate from prototyping to manufacturing."

"We are integrating more open-source systems in our polymer materials."

"We are seeing strong growth across most industries. We expect further investment over the next few years to further our offering and add to our whole package (i.e., AM, vacuum casting, CNC machining, paint/finishing, and traditional modelmaking)."

"We are focused on growing post-processing much more in 2023."

"Lots of interest from space and oil and gas sectors."

"When a business is small, growth can be large. However, our AM business is still not profitable due to the expensive nature of AM systems, compared to CNC machines. For the price of one AM machine, we can get five to seven CNC machines."

"The AM parts business has become very competitive over the past five years."

"We are adding two new materials with 100% recyclability to our portfolio."

"PA11 and PA12 have proved to be of great value to our sales. Our average order size has gone up primarily because of larger polymer PBF orders."

"We're improving fused deposition modelling (FDM) profitability using lower-cost materials from Argyle Materials."

"Many new metals were developed in our lab in 2022."

"We plan to purchase a metal AM system and considering an HP MJF machine."

"We are looking more into PBF. Also, we are focused on certification programs, workforce development, innovating new manufacturing methods, and standardization."

Investment in publicly traded companies

by Brian Drab and Blake Keating

AM companies started the year facing significant headwinds, including supply chain challenges and continuing inflation. Exiting 2022, these disruptions had diminished somewhat, but macroeconomic uncertainty and recession fears are weighing on demand for AM technology in early 2023. Despite the challenging backdrop, most public AM companies still expect to achieve organic sales growth and higher margins in 2023.

Several AM companies referred to 2022 as an "investment year," which included revamping product portfolios, making strategic technology investments, and improving operational efficiencies. Many industry executives continue to cite recent supply chain disruptions as a growth catalyst for additive technologies. This is because AM can provide manufacturing flexibility and resiliency, digitize inventory libraries, and allow companies to restore their procurement activities.

3D Systems and Stratasys continue to be the largest AM companies in terms of market capitalization, at about $1.5 billion and $1.0 billion, respectively. Desktop Metal ($700 million), Velo3D ($600 million), and Materialise ($500 million) are not far behind.

Shares of publicly traded AM companies were down significantly in 2022. 3D Systems' shares began 2022 at $24 and dropped roughly 66% to $7. Other AM companies followed a similar trend in 2022, with Stratasys shares down 52%, Desktop Metal down 73%, Markforged down 78%, and Velo3D down 77%. A major reason for the underperformance was the surge in interest rates weighing on higher growth stocks, particularly for unprofitable and less-mature AM companies. Other reasons included supply chain disruptions in component shortages, continuing inflation leading to higher input costs, and softer demand in many end markets.

Valuations began to recover in 2023, with most of the public companies' shares up in March (3D Systems up 54%, Stratasys up 20%, and Desktop Metal up 65%). However, share prices remain about 55% below levels entering 2022 for the group.

AM stock prices generally underperformed in the broader market indices in 2022. For the year, the Dow Jones Industrial Average was down 9% and the S&P 500 was down 19%. As of the close on March 3, 2023, the Dow was up about 1% and the S&P 500 was up 5% year-to-date in 2023. These changes in the major indices provide reference points when comparing the changes in AM company stock prices.

At the midpoint of the company's guidance, 3D Systems is expecting about 4% organic sales growth in 2023 and about a 100-basis-point improvement in gross margin. Stratasys' expectations are similar, with management forecasting about 3% organic sales growth and a 50-basis-point improvement in gross margin. Several smaller AM companies have more ambitious growth expectations. Velo3D is anticipating sales growth of about 55% in 2023, and Desktop Metal is expecting about 12% sales growth. Gross margin is expected to improve in 2023 for most AM companies as supply chain pressures decline, which should help several less mature AM companies move closer to profitability.

Supply chain pressures and inflation were headwinds for 3D Systems during most of 2022. The rapid rise in inflation reduced consumer demand for a variety of elective medical procedures. This particularly affected 3D Systems' dental aligner business, which was down about 10% in 2022 (and is expected to decline about 35% in 2023). The company's remaining end markets remain relatively healthy, with management expecting all non-dental sales to grow at a mid-teens rate in 2023. Industrial customers have become more cautious around economic uncertainty and started to defer new investments in equipment and inventory in 2022. This is likely to continue into 2023. 3D Systems' revenue grew 3% organically in 2022.

Stratasys faced similar headwinds in 2022, resulting in some order deferrals, particularly in the second half of 2022. Management is still seeing this type of behavior early in 2023. Stratasys' revenue grew 11% organically in 2022 to $652 million and is now similar to 2019 revenue. Management guidance for 2023 implies about 3% organic growth excluding revenue divested with the sale of MakerBot. Stratasys has reported six consecutive quarters of positive earnings and expects adjusted earnings per share (EPS) to be in a range of $0.12 to $0.24 for 2023 (up 20% at the midpoint year-over-year).

Less mature AM companies also struggled with macroeconomic headwinds in 2022. Markforged revenue increased 11% year-over-year in 2022 but is expected to be up only about 5% in 2023 (based on the midpoint of management's guidance). Supply chain disruptions have weighed on Markforged's roll out of the FX20 printer (introduced in 2022) and on gross margin (down 720 basis points year-over-year).

Velo3D's revenue growth has remained robust, up 194% in 2022. Demand remained strong for the company's Sapphire printers, particularly the Sapphire XC, with the Sapphire XC 1MZ starting to ramp up near the end of 2022. However, supply chain issues resulted in higher input costs throughout 2022 and negatively impacted gross margin, which declined from 18.1% in 2021 to 3.6%, in 2022. Velo3D management, however, expects a strong rebound in gross margin in 2023.

In 2022, 3D Systems invested heavily in the company's regenerative medicine business. Management believes the future impacts of the regenerative medicine business will become apparent over the next two years. 3D Systems also launched the SLA 750 and SLA 750 Dual, aimed at large-format, high-volume polymer applications. These printers have been shipped to customers in the aerospace, automotive, and other industrial sectors. 3D Systems also refreshed the ProJet MJP 2500W Plus, which is suited for jewelry and other small precision casting applications.

Stratasys continues to make progress in key markets, such as dental and healthcare. It recently launched TrueDent, a new resin for dentures exclusively compatible with the company's J5 DentaJet. In 2022, Stratasys invested in Axial3D, an artificial intelligence (AI)-driven 3D printing platform that helps healthcare providers segment computed tomography (CT) and magnetic resonance imaging (MRI) scans for anatomic models. Stratasys expects new opportunities for materials in 2023 through the company's Covestro acquisition (expected to close in the second quarter of 2023). In May 2022, Stratasys entered into a business combination agreement with Ultimaker. The deal resulted in a new entity that combines Stratasys' MakerBot business with Ultimaker, to be known going forward as UltiMaker. The business combination was completed in September 2022. Stratasys owns 46.5% of the combined company, while Ultimaker owns 53.5%.

Nano Dimension is expected to report about $40 million in revenue for 2022 based on the current quarterly run rate of $10 million in sales. Although quite small, the company has amassed significant cash and could continue to make acquisitions that change the landscape of the AM industry. Nano Dimension completed 11 stock offerings since February 2020 that collectively added over $1.5 billion in cash to the company's balance sheet. Nano Dimension has acquired five companies in the last two years for a total of roughly $200 million, split between cash and stock. The company also purchased a minority interest in Stratasys in 2022 and now owns roughly 14% of the outstanding ordinary shares. In March 2023, Nano Dimension announced an offer to acquire Stratasys for $18 per share, representing an enterprise value of about $875 million.

Protolabs (PRLB) is a provider of low-volume parts made primarily with injection molding and CNC machining. The company acquired FineLine Prototyping in 2014 and portions of Alphaform AG in 2015. Both companies were AM service providers. In January 2021, Protolabs acquired online manufacturing platform Hubs, formerly 3D Hubs, for $280 million using a combination of cash and stock. Hubs grew over 50% organically in 2022, contributing about $49 million in revenue. AM services accounted for about one-third of Hubs' revenue at the time of the acquisition. Protolabs trades on the New York Stock Exchange (NYSE).

In recent years, several private competitors have garnered significant interest from the investment community, and some of them have captured substantial market share. Three of these companies, Desktop Metal, Markforged, and Velo3D, are now public, all listed through special purpose acquisition companies (SPACs). Carbon and Formlabs have raised significant funding in investment rounds. We are not aware of any initial public offerings across the AM industry in 2022. However, Sakuú, a battery maker using AM technology, has announced plans to go public in 2023 through a SPAC.

In December 2020, Desktop Metal and a SPAC named Trine Acquisition Corp. completed their business combination. Desktop Metal received about $580 million of gross proceeds from Trine's trust account and concurrent equity private placements. The company's stock was trading with a market capitalization of about $700 million as of March 3, 2023.

Markforged was acquired by a SPAC named one in July 2021. The deal valued the company at $1.7 billion and delivered $361 million in gross proceeds to Markforged with net proceeds of

$318 million. The company's stock was trading with a market capitalization of about $300 million as of March 3, 2023. Markforged reported about $101 million in revenue for the full year 2022 and an adjusted operating loss of $63 million. Markforged offers a wide range of printers capable of fabricating metal, polymer, and composite parts. The company's growth has been supported by demand for printers capable of building carbon fiber into parts.

In 2022, Markforged introduced the FX20, the company's largest and fastest printer. The company has more than 200 opportunities with customers in the pipeline, according to management. The company increased FX20 shipments significantly in each quarter of 2022, and FX20 production is expected to reach commercial levels in 2023. Component shortages have materially weighed on the roll out of this new system, as well as putting additional pressure on gross margin.

In September 2021, a SPAC named Jaws Spitfire acquired Velo3D in a deal that valued the company at $1.6 billion. Gross proceeds from the deal were $318 million, and net proceeds totaled $274 million. As of March 3, 2023, Velo3D's stock was trading with a market capitalization of $600 million. The company produces metal AM systems that employ a proprietary printing process.

Velo3D has built a substantial backlog for the company's Sapphire XC printers. This provides strong visibility to the company's revenue target range of $120 million to $130 million for 2023. Velo3D continues to diversify the company's customer base outside of the space industry. It has added customers in the aerospace, automotive, defense, and energy sectors. Customers outside of the space sector now represent about 75% of the customer base exiting 2022. The same year, Velo3D's customer base grew more than 50%, implying the company ended 2022 with more than 27 customers. More than half own more than one Sapphire system.

Carbon has raised over $680 million in funding and, at one point, was valued at more than $2 billion. The company has had success in the sporting goods industry, serving customers such as Adidas, Rawlings, and Specialized. In recent years, the company has become an important player in the dental aligner market. We believe Carbon achieved significant revenue growth in 2021 and 2022.

Formlabs has experienced strong growth since the early stages of the pandemic. The company has raised over $250 million and was valued at $2 billion in the latest funding round. Since inception, Formlabs has sold over 100,000 printers, most of which were sub $5,000 desktop units. The company's strong gross margin is supported by both system sales and a relatively high-margin consumables revenue stream.

Sakuú and a SPAC named Plum Acquisition Corp. announced a business combination agreement that will make Sakuú a publicly traded company. As of March 19, 2023, the deal had not yet closed. The estimated enterprise value of the transaction is $705 million. Sakuú is commercializing next-generation lithium-ion batteries using the company's Kavian AM platform.

Revenues and earnings

Stratasys generated revenue of $651 million in 2022, up 7% from $607 million in 2021. Product revenue (systems and consumables) increased 8% year-over-year. Revenue from the product segment represented 69% of fiscal 2022 sales. Service revenue at Stratasys increased 5% year-over-year. Adjusted gross margin expanded 20 basis points to 48% in 2022. Product gross margin contracted 160 basis points to 54.7% and remains roughly 700 basis points below pre-pandemic levels.

Services gross margin at Stratasys expanded 350 basis points to 32.8% and is in line with the 2019 segment gross margin. Adjusted operating margin improved 240 basis points to 2.1%, reaching management's target for the year of greater than 2%. Operating expenses increased by 2% in 2022 but were down 220 basis points as a percentage of sales due to operational efficiency improvements. Stratasys reported adjusted EPS of $0.15, up $0.22 from the -$0.07 reported in 2021.

Stratasys provided 2023 guidance, anticipating revenue in the range of $620 million to $670 million. This translates to an increase of 3% year-over-year when MakerBot revenue in 2022 is excluded. Gross margin is expected to be flat or up modestly compared with 2022. Operating expenses are expected to improve as a percentage of revenue. As a result, the operating margin was forecast at about 3.0% for the year, and adjusted EPS are expected to be between $0.12 and $0.24, up 20% at the midpoint year-over-year.

3D Systems reported a generated revenue of $538 million in 2022, down 13% from $616 million in 2021. Excluding divestitures and foreign currency translation, revenue was up 3% year-over-year, driven by 3% organic growth in healthcare and 10% organic growth in industrial businesses. In 2022, adjusted gross margin contracted 320 basis points to 39.8%. Product gross margin contracted about 300 basis points, and services gross margin contracted 150 basis points. The company's adjusted operating margin decreased by 1,300 basis points year-over-year to a negative 5%. 3D Systems reported an adjusted loss per share of $0.23 in 2022, down $0.22 from an adjusted EPS of $0.45 in 2021.

3D Systems' management provided guidance for revenue, gross margin, and adjusted interest, taxes, depreciation, and amortization (EBITDA) for 2023. Revenue is expected to be within a range of $545 million to $575 million, up about 4% at the midpoint. Gross margin is anticipated to be 40–42%, up about 100 basis points year-over-year at the midpoint. Management expects adjusted EBITDA and free cash flow to break even or better for 2023. The 2023 guidance takes account of two headwinds. One of them is the expenses associated with investment in the regenerative medicine business, which will be $9 million higher than in 2022. The second is a continued decline in dental orthodontics demand.

Desktop Metal's revenue was $209 million in 2022, up about 86% year-over-year, driven by contributions from acquisitions. The company reported an adjusted EBITDA loss of $118 million in 2022. For 2023, management expects sales to be in a range of $210–260 million, up 12% at the midpoint. Management anticipates adjusted EBITDA to be in a range of a negative $50 million to a negative $25 million for 2023. It also expects to reach adjusted EBITDA breakeven before year-end. Desktop Metal has a global installed base of over 7,000 units.

SLM Solutions is expecting at least a 33% increase in revenue to €100 million in 2022. The company expects to be adjusted EBITDA breakeven for the second half of 2022 on a quarterly basis. Nikon, the Japanese optical instruments company, made an all-cash takeover bid for SLM at €20 per share, valuing the company at €622 million. The acquisition was completed on January 20, 2023.

Markforged reported 2022 revenue of $101 million, up 11% year-over-year. Adjusted EBITDA was a negative $60 million in 2022, down from a negative $38 million in the prior year. Adjusted gross margin for 2022 was down 720 basis points year-over-year to 50.8%. Management's guidance for 2023 revenue was in a range of $101–110 million, which is up 5% year-over-year at the midpoint. The company now has a printer installed base of over 12,000 units.

Materialise revenue increased 13% to €232 million in 2022. The company reported a net loss of €2 million and adjusted EBITDA of roughly €19 million, which is 8.2% of revenue. Management provided revenue and EBITDA guidance for 2023. Revenue is expected to be in a range of €255–260 million, up 11% year-over-year at midpoint. Adjusted EBITDA is expected to be in a range of €25–30 million, up 45% at midpoint.

Protolabs' 2022 revenue of $488 million was relatively flat year-over-year (up 3% organically). Analysts project revenue growth of 1% in 2023. Adjusted EPS decreased 3% in 2022 and are projected by analysts to decrease 23% in 2023. 3D printing revenue at Protolabs grew 9% in 2022 to $79 million, accounting for 16% of total company revenue.

Velo3D generated $81 million in revenue in 2022, up 194% year-over-year. Gross margin in 2022 was 3.6%, down from 18.1% in 2021. Adjusted EBITDA was a negative $77 million, down about $31 million from the prior year. This was largely due to lower gross margin, which was impacted by supply chain disruptions and higher material costs. Management provided 2023 revenue guidance in a range of $120–130 million, equating to about 55% year-over-year growth at the midpoint. Gross margin for the full year is expected to be in a range of 19–21%, up about 1,600 basis points at the midpoint. Management expects gross margin to increase sequentially throughout the year, with 30% within reach in the fourth quarter 2023. The consensus estimate of 2023 gross margin is 19.3%.

Voxeljet guided 2022 revenue was €25–30 million, up 11% year-over-year at the midpoint. The company expects gross margin to be above 32.5%. Consensus estimates forecast 31% revenue growth and gross margin of 34.8% for 2023.

The following table highlights the consensus revenue and EPS estimates for the companies covered in this section of the report.

Revenue consensus	2022 sales[1] (millions)	2023E sales[2] (millions)	2024E sales (millions)	2023E % Growth	2024E % Growth
3D Systems	$538	$557	$601	4%	8%
Stratasys	$651	$642	$696	-1%	8%
Desktop Metal	$209	$237	$277	13%	17%
Protolabs	$488	$493	$517	1%	5%
Materialise	$249	$271	$303	9%	12%
Markforged	$101	$107	$130	6%	21%
Velo3D	$81	$124	$182	54%	47%
Voxeljet	$28	$36	$44	31%	21%
EPS consensus	**2022 EPS**	**2023E EPS**	**2024E EPS**	**2023E % Growth**	**2024E % Growth**
3D Systems	$(0.23)	$(0.16)	$(0.01)	NM	NM
Stratasys	$0.15	$0.15	$0.37	1%	146%
Desktop Metal	$(0.42)	$(0.20)	$(0.09)	NM	NM
Protolabs	$1.50	$1.16	$1.23	-22%	6%
Materialise	$(0.04)	$0.01	$0.17	NM	NM
Markforged	$(0.31)	$(0.28)	$(0.18)	NM	NM
Velo3D	$(0.41)	$(0.26)	$(0.09)	NM	NM
Voxeljet	$(2.33)	$(2.95)	$(3.74)	NM	NM

1 2022 numbers are all actual reported results except for Voxeljet, which is based on consensus estimates.

2 All forecasted figures reflect consensus estimates.

Notes: All figures are in U.S. dollars. NM means "not meaningful."

Source: FactSect and company reports

Two of the most common valuation metrics used by growth investors are the price/earnings (P/E) and enterprise value/EBITDA (EV/EBITDA) multiples. The P/E is calculated by dividing the stock price by the consensus EPS estimates. EV/EBITDA is defined as a company's market capitalization plus net debt (debt minus cash) divided by earnings before taxes, interest, depreciation, and amortization. The following tables highlight P/E and EV/EBITDA valuations as of March 9, 2023.

Company	Ticker	Price	EPS		P/E	
			CY 23E	CY 24E	CY 23E	CY 24E
3D Systems	DDD	$10.32	$(0.16)	$(0.01)	NA	NA
Stratasys	SSYS	$14.09	$0.15	$0.37	93x	38x
Desktop Metal	DM	$2.19	$(0.20)	$(0.09)	NA	NA
Protolabs	PRLB	$33.51	$1.16	$1.23	29x	27x
Materialise	MTLS	$8.41	$0.01	$0.17	NA	50x
Markforged	MKFG	$1.13	$(0.28)	$(0.18)	NA	NA
Velo3D	VLD	$2.65	$(0.26)	$(0.09)	NA	NA
Voxeljet	VJET	$2.18	$(2.95)	$(3.74)	NA	NA
Average					61x	38x
Company	**Ticker**	**Price**	**EBITDA**		**EV/EBITDA**	
			CY 23E	CY 24E	CY 23E	CY 24E
3D Systems	DDD	$10.32	$2	$24	NM	NM
Stratasys	SSYS	$14.09	$42	$58	15x	11x
Desktop Metal	DM	$2.19	-$45	-$9	NM	NM
Protolabs	PRLB	$33.51	$69	$72	13x	12x
Materialise	MTLS	$8.41	$28	$43	15x	10x
Markforged	MKFG	$1.13	-$50	-$23	NM	NM
Velo3D	VLD	$2.65	-$44	-$10	NM	NM
Voxeljet	VJET	$2.18	-$10	$0	NM	NM
Average					14x	11x

Notes: All figures are in U.S. dollars. NM means "not meaningful."

Source: FactSet and company reports

Several publicly traded AM companies are not yet profitable in terms of EBITDA or EPS. This is either because they are still in the early stages of growth or have experienced operational challenges. In this situation, investors will often value a company in terms of a multiple of sales, specifically the enterprise value-to-sales ratio. The following table provides valuation multiples on this basis for 2023 and 2024 sales estimates.

Company	Ticker	Price	Sales (millions)		EV/Sales	
			CY 23E	CY 24E	CY 23E	CY 24E
3D Systems	DDD	$10.32	$557	$601	2.2x	2.1x
Stratasys	SSYS	$14.09	$642	$696	1.0x	0.9x
Desktop Metal	DM	$2.19	$237	$277	2.6x	2.2x
Protolabs	PRLB	$33.51	$493	$517	1.7x	1.7x
Materialise	MTLS	$8.41	$271	$303	1.6x	1.4x
Markforged	MKFG	$1.13	$107	$130	0.9x	0.7x
Velo3D	VLD	$2.65	$124	$182	3.8x	2.6x
Voxeljet	VJET	$2.18	$36	$44	0.9x	0.7x
Average					1.8x	1.5x

Source: FactSet and company reports

Several, generally smaller, AM companies are listed on international exchanges. The table below includes share prices as of March 3, 2023, and the company's 2022 sales (local currency).

Company	Ticker	Price	CY2022 Sales (millions)
3DM Digital Manufacturing Ltd.	DM3-IL	ILS 2.69	NA
Amaero International Ltd.	3DA-AU	AUD 0.16	AUD 0.8
AML3D Ltd.	AL3-AU	AUD 0.08	AUD 1.9
Aurora Labs Ltd.	A3D-AU	AUD 0.03	AUD 0.1
Freemelt Holding AB	FREEM-SE	SEK 7.98	SEK 36.1
Massivit 3D Technologies Ltd.	MSVT-IL	ILS 6.74	NA
Nano Dimension Ltd. Sponsored ADR	NNDM	USD 3.10	USD 40.0
Prodways Group SA	PWG-FR	EUR 2.78	EUR 80.6
Titomic Ltd.	TTT-AU	AUD 0.15	AUD 4.2
Xi'an Bright Laser Technologies Co. Ltd. Class A	688333-CN	CNY 153.31	NA

Source: FactSet and company reports

Several AM stocks have received significant short interest. As of March 6, 2023, 8% of 3D Systems' outstanding shares were sold short, meaning that investors are betting the stock price will decline. This compares to 22% for Desktop Metal, 6% for Velo3D, 4% for Protolabs, and 2% for Markforged.

Looking ahead

The value of AM company shares generally declined in 2022. This was largely a result of an overall market decline and a shift in investor sentiment driven by inflation and recession fears. Shares of AM companies recovered somewhat in early 2023, but on average, shares were down over 50% from early 2022 levels. Through March 3, 2023, shares of 3D Systems, Stratasys, Desktop Metal, Markforged, and Velo3D were up 54%, 20%, 65%, 32%, and 80% year-to-date, respectively. Relative to all-time historical high share prices, shares are down about 87% on average for the group.

Several questions and considerations may be on the minds of investors. For example, what will the near-term impact of recession fears and higher interest rates be on the industry? Also, what is a sustainable long-term organic revenue growth rate for the industry and its current leaders?

Both 3D Systems and Stratasys are investing in new technology development and more strategic customer engagement. Earlier-stage companies, such as Markforged and Velo3D, are primarily focused on bringing new technology to market and optimizing manufacturing operations. Legacy and less mature companies will likely continue to face increased competition from new competitors.

It is likely that market dynamics in 2022 discouraged several AM companies from attempting to go public. Over the next two or three years, we believe more fast-growth private companies will file for initial public offerings.

Mergers and acquisitions

by Shamil Hargovan and Henry Ma

Healthcare applications, strategic supply chains, and metal applications in the aerospace and automotive sectors were prominent targets for AM investment in 2022. The numbers and values of mergers and acquisitions (M&As) declined from 2021.

The industry recorded 21 AM-related acquisitions from March 1, 2022, to February 28, 2023. To be included in the following table, AM was a predominant or significant part of the business of the acquired company. As many as 54 M&A transactions were recorded in 2021 and 27 in 2020. The financial details of many of these transactions were not published. Healthcare- and aerospace-related deals commanded the highest valuations. The total value of the recent period of deals is estimated at $868.25 million.

Leading AM companies 3D Systems and Stratasys have been active in M&A. One of the most significant of the year was Stratasys' acquisition of the AM photopolymer business of Covestro. 3D Systems acquired Kumovis and dp polar. Markforged acquired Digital Metal, a BJT system manufacturer formerly owned by Höganäs, a Swedish producer of metals. Nano Dimension acquired ceramic printing companies Admatec and Formatec.

Company	Investor	$M
March 2022		
Advant Medical	UFP Technologies	$21.2
April 2022		
Kumovis	3D Systems	$44.2
Teton Simulation	Markforged	–
Luxexcel	Meta Platforms	–
May 2022		
Allegro 3D	BICO Group	$11.0
Hogrotec	Liqtra	–
Printed Solid	Prusa Research	–
June 2022		
Gen3D	Altair Engineering	–
Technology Assessment & Transfer	SINTX Technologies	$0.8
July 2022		
Digital Metal	Markforged	$33.5
Formatec Holding B.V	Nano Dimension	$12.9
ZMorph	Sygnis	–
August 2022		
Covestro (AM photopolymer division)	Stratasys	$43.7
dp polar	3D Systems	–
ParaMatters	Carbon	–
September 2022		
Condale Plastics	Lifco	–

Company	Investor	$M
Identify3D	Materialise	–
October 2022		
CerAMing	Lithoz	–
Riven	Stratasys	–
January 2023		
Dinsmore	AddMan Engineering Group	–
Global3D	Singular Health Group (ASX: SHG)	$0.6
SLM Solutions Group	Nikon	$665.6
Taulman3D	Braskem	–
February 2023		
Gefertec	Berlin Industrial Group (BIG)	–

We expect to see continued consolidation across machine manufacturers and material providers. Service providers are aiming for greater flexibility and increased share of the AM market. Some public companies will attempt to go private as public market share prices decline. Typically, these companies will take on additional assets and aim to go public a second time or be acquired by a strategic buyer. Given tightening monetary policy and deteriorating sentiment, AM industry deals in 2023 and beyond will require sticking to business fundamentals. Companies perceived as running a lean operation will continue to attract a range of buyers.

In early March 2023, Nano Dimension made an offer to acquire all outstanding shares of Stratasys at a premium of 36% above the Stratasys stock price on March 1, 2023. Stratasys declined the offer. In July 2022, Nano Dimension had accumulated 12% of Stratasys' stock in open market trading.

Corporate investments

Corporate investments in AM reveal continuing confidence in the future of the technology. Without them, the development and commercialization of products and services and the adoption of AM would be slow. In 2022 and early 2023, companies around the world continued to invest in AM projects, facilities, and systems. The following are among the leading projects:

- 6K Additive is expanding its powder production facility in Burgettstown, Pennsylvania by 3,252 m^2 (35,000 ft^2). The company is seeing increased demand for its nickel, titanium, and refractory powders for AM applications.
- Boeing inaugurated its Center of Additive Manufacturing Excellence in September 2022. The facility, located in Auburn, Washington, produces aerospace parts using AM.
- Castheon is occupying a new $20 million facility that supports increased production of parts for space and hypersonic applications. The company specializes in printing refractory alloys.
- Collins Aerospace is opening an AM center at its maintenance, repair, and operations facility in Monroe, North Carolina. It is one of 75 facilities Collins Aerospace operates worldwide.

- GKN Aerospace has created an AM center of excellence in Fort Worth, Texas, which became operational in early 2023. The 9,290-m^2 (100,000-ft^2) facility is being used for the development and production of large titanium parts for aerospace.
- Renishaw, the British metrology, engineering equipment, and AM systems manufacturer, is investing £50 million ($60 million) to expand manufacturing capacity at its South Wales plant. The facility is used for producing a range of the company's products, including AM systems.
- Safran, the French aerospace giant, has inaugurated an AM center of excellence in Le Haillan, near Bordeaux in southwest France. The 12,500-m^2 (134,550-ft^2) center employs 100 engineers and technicians. The company has invested €80 million in the center, which includes money from the regional government.
- Sakuú opened a 7,340-m^2 (79,000-ft^2) facility in San Jose, California in August 2022. It serves as a development center for an AM-driven battery production process. The facility is paving the way for scaling the process in California and elsewhere.
- Stryker has expanded its AM manufacturing facility by 14,500 m^2 (156,000 ft^2) in County Cork, Ireland. The medical technology company expects the development will add up to 600 jobs to the region.

CAD solid modeling

by Randall S. Newton

Solid modeling for mechanical and product design is a mature technology. Computer-aided design (CAD) software updates focus on usability, interoperability, and downstream uses of data. Recent developments include advancements in 3D virtual environments, increased use of upfront simulation in design, and improved workflow through model-based design.

In 2022, demand for solid models as digital twins in 3D virtual environments increased substantially. Four vendors are engaged in strong competition for dominance in creating industrial digital twin platforms. Only one is a traditional CAD software company.

Unreal Engine, a division of Epic Games, and Unity initially targeted the gaming industry with platforms for building interactive worlds. Today's leading game engines work in 3D and offer players complex play environments. In a game, 3D objects and landscapes are used to create the images displayed in an imaginary world. However, game engines typically cannot display real-world objects and infrastructure with the accuracy demanded by engineers and architects.

Unreal Engine and Unity both created new versions to focus on real-world 3D spaces for product design and architecture as their first target market. Today, both companies work with CAD solid models for product design and architectural building information models. Both turned to external partners to gain the necessary technical expertise needed to support CAD data.

Nvidia is best known for its graphics acceleration boards, which have revolutionized 3D graphics applications, engineering simulation, and artificial intelligence. Nvidia offers Omniverse, a real-time 3D graphics collaboration platform. Example uses include a real-time digital twin of the Deutsche Bahn rail network and a corrosion simulation model of a heat-recovery steam generator at Siemens Energy. The platform is also being used by the UK Atomic Energy Authority to design and develop a full-scale nuclear fusion reactor.

Fig. 171. Design and development model of a full-scale nuclear fusion reactor, courtesy of Nvidia.

The fourth company competing in the digital twin platform market is Dassault Systèmes, the company behind SolidWorks and CATIA. It was one of the first to support large-scale 3D digital environments for design. Its 3DEXPERIENCE brand is now a major driver of innovation throughout the company.

CAD tools define the shape and geometric features of a product, whereas computer-aided engineering (CAE) simulation tools define the physics of a product. CAD vendors are continuing to invest in bringing more upfront CAE tools into the CAD environment. One of these tools is design for AM, which has become an important R&D topic for several CAD vendors.

Many manufacturing companies used the downturn in business caused by the pandemic to update their technology-dependent workflows. Perhaps the largest beneficiary of this was model-based design (MBD). This approach to CAD modeling ensures that all data needed to define a product is included in the digital model. Using MBD means that the 3D model becomes the authoritative information source for everyone in the organization. Any 2D details or bills of materials needed by the shop floor are extracted from the 3D model and are not manually generated. Simulation, CNC machining, and AM are performed using data from the same model. More work needs to be done to create a seamless two-way flow of data for all applications. Many customers are keen to see this happen.

CAD vendors do not report seat counts with their quarterly revenue reports. For this reason, unit sales growth is estimated based on revenue statements. Estimates for the four largest CAD companies are shown in the following table. These figures include worldwide sales revenue, net income, and the estimated number of commercial CAD seats sold in 2022. They also include the estimated cumulative total number of CAD seats sold through the end of 2022.

Company	2022 revenue (millions $)[1]	2022 net income (millions $)[1]	2022 commercial seats (000s)[2]	Cumulative commercial seats (000s)[2]
Autodesk	5,010	823	Inventor: 43	865
Dassault Systèmes	6,056	347	CATIA: 104 SolidWorks: 145	1,292 1,418
PTC	1,930	313	Creo: 29	639
Siemens PLM Software	–	–	NX: 55 Solid Edge: 54	842 527
Total	**–**	**–**	**430**	**5,583**

Footnotes:

1 Revenue and net income reported is for the entire company and not exclusively for solid modeling products and services. CAD is such a small portion of Siemens total revenue that it is not reported separately.

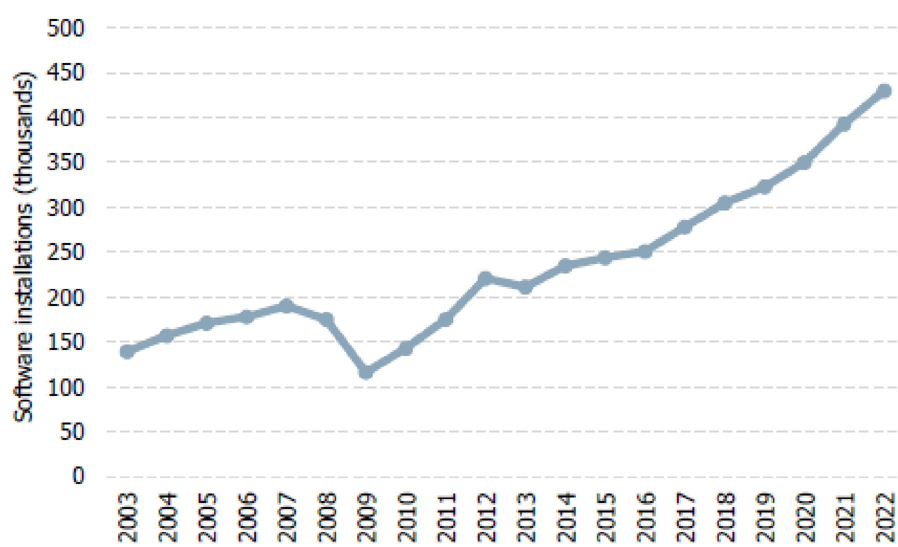
2 Educational seats–sold or given away–are not included.

Note: The table excludes Alibre Design, Cobalt, IronCAD, KeyCreator, Onshape, SpaceClaim, and other CAD software products. Also, these totals exclude other 3D products capable of generating 3D models for AM including Autodesk Alias Studio, Rhino, and others.

Source: Consilia Vektor and Wohlers Associates

The following graph shows commercial CAD software installations (in thousands) over the past 20 years. After a low point in 2009, sales have risen consistently, except for a small decline in 2013. In 2022, sales were an estimated 430,000, an increase of 9.4%. Growth was 12.3% in 2021 and 8.4% in 2020.

Fig. 172. Number of commercial CAD software installations; source: Consilia Vektor and Wohlers Associates



PART 4: PRODUCTION OF END-USE PARTS

Additive manufacturing (AM) is growing in recognition as a mainstream option for series production applications. It eliminates the need for costly tooling such as molds and dies and can produce highly complex parts. AM makes possible small batch production, custom products, lightweight structures, complex internal features, and the consolidation of many parts into one.

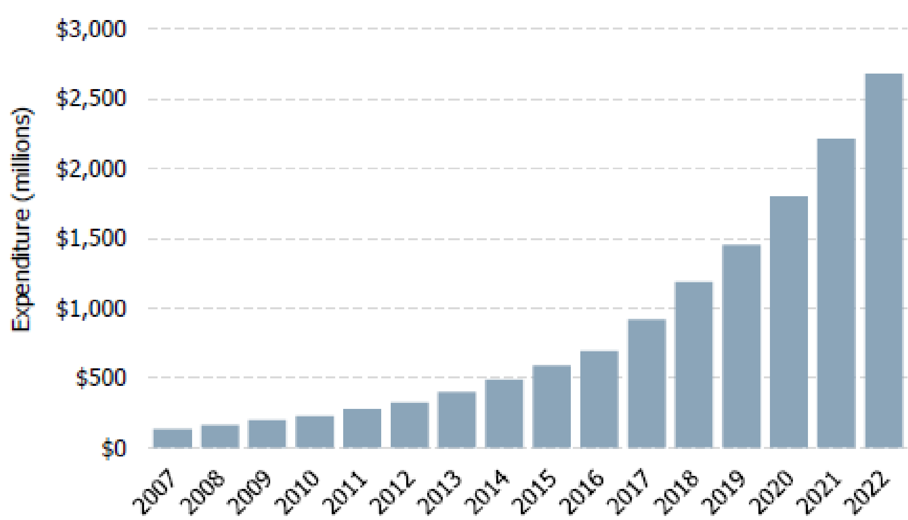
Concerning AM for final parts production, Wohlers Associates asked companies, "By what percentage did this segment of your business grow in 2022?" A total of 119 service providers and 128 manufacturers of industrial AM systems responded. The responses were averaged, as shown in the following.

Year	Growth	Year	Growth
2008	19.9%	2016	18.0%
2009	22.8%	2017	32.4%
2010	14.2%	2018	29.2%
2011	22.4%	2019	22.5%
2012	17.9%	2020	23.9%
2013	22.6%	2021	22.8%
2014	22.7%	2022	21.2%
2015	20.6%		

Source: Wohlers Associates

The same information was used to estimate the amount of money spent annually on end-use part production worldwide. This is shown in the following graph with values in millions of dollars. An estimated $2.679 billion was spent on AM parts for end-use products in 2022, up 21.2% from the year before. This represents revenue produced by service providers worldwide. It excludes the value of end-use parts made by manufacturing companies that are not service providers.

Fig. 173. Global expenditure on final part production; source: Wohlers Associates



Metal AM is having an interesting impact on the production of certain product types. The parts often offer similar or better material properties than those made with conventional processes, such as casting. Metal AM can reduce the use of material, generate less waste, and lower a part's weight. It is often ideal for high-value, low-volume production of complex parts across several sectors, including aerospace, healthcare, dentistry, energy, and motorsports.

Benefits of AM

AM becomes a candidate for final part production when it adds value compared to parts made by conventional manufacturing processes. Manufacturers are willing to consider a new production process when it is significantly less expensive and/or improves value and product performance. AM can provide these benefits by affecting key aspects of product development and manufacturing, including:

- Biomimicry and generative design
- Custom and limited-edition products
- Design changes after production has begun
- Digital inventories and on-demand manufacturing
- Lightweight parts
- Optimized structures
- Part consolidation, partly to reduce or eliminate assembly
- Reduction of lead times, part numbers, and labor
- Reduction or elimination of tooling
- Same process and material for prototyping and production
- Waste reduction and sustainability

Biomimicry and generative design

AM technology is developing continually and new design methods are evolving to take advantage of these developments. The design freedom offered by AM creates an opportunity for advanced designs not practical in conventional manufacturing. Design tools are developing and available that "unlock" these opportunities.

Generative design is an interesting new method for product development. The approach uses computer algorithms that automatically generate many variations of a design. These variations are based on specific inputs such as material type and load requirements. The software generates hundreds, even thousands of versions of a proposed design, from which the software and designer find the best result.

Biomimicry is the design of structures modeled after those found in nature. It imitates elements of nature that have evolved over thousands of years, often resulting in strong and lightweight geometric shapes and features. As more is learned about mimicking nature's designs, new computational methods and design tools will develop to replicate these features. The AM industry has barely scratched the surface of what is possible surrounding biomimicry.

The bicycle saddle in the following image resulted from an exploration into organic structures that optimize seating. The design was inspired by plant cell structures. The saddle adapts to a person's shape and is manufactured using a single material.

Fig. 174. Nature-inspired bicycle saddle, courtesy of Lilian van Daal

Custom and limited product manufacturing

Products are not always "one size fits all." Rather than using adapters or manually customizing products, AM can be used to produce custom products digitally. Mass customization provides consumer benefits by tailoring each part to satisfy specific interests and needs. This applies to orthotics, medical implants, footwear, eyewear, handles and grips, nameplates, and many other products. The following image shows a custom "moonboot" cast. It was manufactured using a powder bed fusion (PBF) system from EOS.

Fig. 175. Custom moon boot, courtesy of Olaf Diegel

Digital inventories and part consolidation

Just-in-time operations result in small part inventory. AM reduces inventory by consolidating many parts into one and from on-demand manufacturing. These two attributes reduce the need for on-site storage and off-site warehousing. By reducing inventory, companies free up capital, providing more flexibility to develop new products and invest in other areas.

Reducing the number of parts in an assembly immediately reduces the cost and time associated with manufacturing, inspection, documentation, and production planning and control. Also, reduced part count results in a reduction of time and labor to assemble the product. The "footprint" of an assembly line becomes smaller, further cutting costs.

Elimination of tooling

Unlike plastic injection molding and metal casting, AM does not require tooling to produce a part. This can reduce cost and lead time and accelerate time to market. AM can also eliminate production delays due to damaged or worn tools and maintenance. AM systems have maintenance costs and downtime, but issues associated with tooling do not apply to AM.

Optimized structures

AM empowers engineers and designers to optimize strength, stiffness, weight, manufacturability, and other parameters. Software tools are available to supplement traditional CAD in this process. These tools include topology optimization (TO), finite element analysis (FEA), and scripting-based design software.

Fig. 176. Robot arm segment optimized for strength and weight, courtesy of nTopology

Reduced lead time and on-demand manufacturing

Having the option of quickly changing a product's design on short notice is another benefit of AM. Every part built on an AM machine can be different, so parts can be made to order. Manufacturers can react more quickly to changing market conditions and production rates can vary to match demand.

Careful metering of production volumes can result in just-in-time manufacturing. As AM supply chain integration matures, the production workflow will become better understood. In practice, however, delays associated with AM can still occur. Delays may include data preparation, time required for cooling, part finishing, and other forms of post-processing. Even with these constraints, using AM can result in an impressive reduction in lead time and increase in on-demand manufacturing.

Using AM for on-demand production is perhaps best seen with spare parts. When mechanical assemblies are made up of thousands of unique parts, fabricating, tracking, and storing spare parts is costly. This is especially true if only a few spare parts are deployed during the life of an assembly. Transporting spare parts to and from a warehouse can become a bottleneck. Printing a spare part as needed from a digital inventory eliminates physical storage. In many instances, digital files can be transmitted and printed at the point of service, eliminating the transportation bottleneck.

The following is a spare part made on demand using AM. It replaces a broken high-power miniature circuit breaker (MCB) release latch mechanism.

Fig. 177. Spare part for high-power MCB release latch mechanism that was broken (top), and printed replacement parts (middle and bottom), courtesy of Olaf Diegel

Waste reduction and sustainability

AM parts can be more environmentally friendly by reducing material waste and/or employing sustainable feedstock. Sustainable materials typically require less energy to produce and have a smaller carbon footprint. They include wood, stone, and other natural materials.

Organizations can reduce energy consumption by producing lightweight AM parts. This applies to most types of vehicles and some stationary equipment. AM can be used to manufacture conventional injection molding tools with high-efficiency cooling channels. This results in less energy required to produce the injection-molded plastic parts.

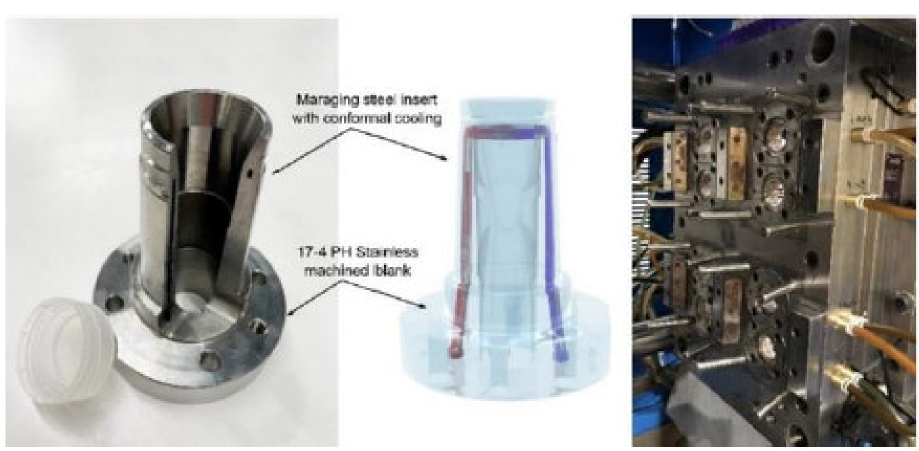


Fig. 178. High-efficiency injection molding tool in which cooling time was reduced from 4.5 to 1.7 seconds, thus greatly reducing energy consumption, courtesy of Simon Chan

Design for additive manufacturing

AM can be an expensive process for series production applications. To be cost-effective, AM must add enough value to offset these high costs. A desire to add product value is the driving force behind design for additive manufacturing (DfAM). This approach to design uses a range of techniques, some of which are tailored to the characteristics of specific AM processes. The aim is to maximize the benefits AM brings while minimizing the cost of part production. If DfAM is done correctly, AM can be a viable and valuable production method for many applications.

Fig. 179. Robot arm extruder bracket in which the majority of the assembly was made from sheet metal and fastened to a more complex 3D-printed part (white), courtesy of Olaf Diegel

AM is not a replacement technology

If AM is to be cost-effective, it is critical to understand it is not a replacement technology for conventional manufacturing. Instead, it is a complementary technology that can add significant product value. With good DfAM practices, a goal is to eliminate as many parts as possible from an assembly. If one or more parts cannot be eliminated, one should decide whether it should be made using AM. In most cases, it is faster and less expensive to use conventional manufacturing. AM should only be considered when it adds value. In such cases, a redesign is necessary.

Another design challenge presented by AM is that it is a near-net-shape process. This means parts from most AM systems do not offer the same level of accuracy and surface finish as conventionally manufactured parts. In many cases, 3D-printed parts must be post-processed to bring them to the level of accuracy and surface finish typically required. This post-processing is usually done using computer numerical control (CNC) machining or with a combination of manual and automated techniques. This usually means that for every industrial AM system purchased, a companion post-processing technology is purchased, although it can often support multiple AM systems. The factory of the future will not use only AM systems, but rather a mix of additive and conventional manufacturing technologies. Making correct decisions about which process combinations to use is key.

Somewhere along the spectrum of geometric part complexity is a point beyond which it is worthwhile to manufacture a part using AM. In general, any part that can be machined on a 3-

axis CNC machine is unlikely to be a viable candidate for AM. It may be possible to make it using AM, but it is often more cost-effective to produce it with conventional processes. One exception is to use AM to overcome supply chain gaps. View AM as another tool in the toolbox and learn when it is the best tool for the job.

Economic benefits of DfAM

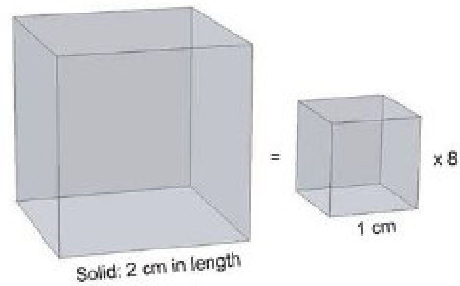
As stated previously, a quick switch from conventional to AM without DfAM misses significant opportunities. Several approaches to design are possible with AM that would otherwise be difficult and/or expensive to achieve with conventional manufacturing. For example, increased geometric complexity does not automatically result in increased production cost as it would with conventional manufacturing. When geometric complexity achieves the use of less material, part cost decreases. This encourages the use of organic features, lattice structures, TO, and surface features and textures.

The most compelling reason for implementing DfAM is simple economics. The arguments made in the following paragraphs apply equally to most AM processes, but are particularly compelling for metal. Consequently, metal AM is used in the examples.

The relationships between part size, material mass, and volume are the most fundamental economic considerations in AM. For example, a doubling in size can represent an exponential increase in price.

A simple cube that measures 1 x 1 x 1 cm (0.4 x 0.4 x 0.4 in) in size represents a volume of 1 cm^3 (0.06 in^3). If the size of the cube is doubled to 2 x 2 x 2 cm (0.8 x 0.8 x 0.8 in), the volume is 8 cm^3 (0.5 in^3), an eightfold increase in volume. The increase means part size, material required, and cost increase eightfold.

Fig. 180. Material volume change of a cube when doubling its size



The same principle applies to the mass of material used in a part. The less material mass, the better, because any unnecessary material can represent an increase in print time and cost.

Consider the previous example of a larger cube of 8 cm^3 (0.5 in^3). If it is hollowed to a wall thickness of 0.44 mm (0.02 in), the outer dimensions double the 1 cm^3 (0.06 in^3) cube. However, the volume of material is only 1 cm^3 (0.06 in^3), which is the same as a solid cube of 1 cm^3 (0.06 in^3). This does not mean the larger shelled cube costs the same as the smaller solid cube. Its increased height means more layers and more recoating time, resulting in overall higher machine cost. However, the cost is substantially lower than that of a solid cube of 2 cm (0.8 in).

With good DfAM practices, it is possible to reduce a part's mass by 30–90% of a similar-sized solid object. This results in greatly reduced part cost, decreased shipping costs, and potentially increased functionality. These techniques are further explained in the following sections.

Calculating part cost

3D printing can be expensive for parts not specifically designed for AM. The reasons are straightforward. Industrial AM systems and materials are expensive and part production speed is relatively slow. A metal AM system can cost more than $1 million. The total investment can exceed this amount when adding support equipment, such as heat treatment furnaces, wire electrical discharge machining (EDM), and CNC machining. What is more, AM materials can cost many times more than for conventional manufacturing.

A metal AM machine can run up to about 80% of the time, which is an estimated 7,000 hours per year. A common return on investment (ROI) period used by industry to recoup the cost of capital equipment is about two years, although it varies from company to company.

The following table shows estimated hourly operating costs of a metal AM system. Depending on the price of the machine and ROI period, the cost can be in the range of $37–90 per hour. For the examples in this section, consider a mid-range machine with an operating cost of $65 per hour.

Machine purchase price	Hourly machine running cost
$500,000	$37.45
$650,000	$48.69
$1,000,000	$74.91
$1,200,000	$89.89

Equation used to calculate costs: *machine hourly running costs = (machine purchase price + interest) / (payback period x percentage running time x annual hours)*

According to this cost model, a single part taking 10 hours to build would incur a machine operation cost of $650. However, metal AM build times are often substantially longer. It is not uncommon for build times to require 40, 60, and even 100 hours. If a part takes 100 hours to print, the machine time cost is $6,500. This highlights the importance of finding methods to reduce the build time. Whenever possible, build multiple parts simultaneously to reduce the cost per part. To gain the most from a system, companies will fully pack the build chamber before starting a new job.

Operational costs for metal AM systems are high. Industrial CNC and injection molding machines can be comparable in price and have similar hourly operating costs. A typical part with few complex features can be CNC machined or injection molded in a fraction of the time it takes to 3D print the part.

Aside from hourly operating costs, material use is a key factor in determining part cost. Aluminum and steel powders for AM are typically in the range of \$78–98 per kg (\$35–45 per lb). Other alloys used for PBF, such as cobalt-chrome and titanium, can be \$300–\$360 per kg (\$136–\$164 per lb). These costs are about 10 times higher than billet material used for machining.

Compared to CNC machining, metal AM typically results in less waste, but AM parts require sacrificial support material. The supports are required for overhangs and to anchor the part to the build platform. The material waste is typically about 10%, including both support material and partially sintered powder that cannot be reused. This compares to 70–90% waste for CNC machining, although it depends on the part shape and features.

Pre- and post-processing costs can be substantial. Some companies estimate pre- and post-processing may represent more than 40% of the total production cost of a metal AM part. The cost of a part that takes 100 hours to produce could rise from \$6,500 to more than \$9,000. This confirms the importance of designing a part that reduces both build and post-processing time.

Some factors in the production of metal PBF parts, such as layer recoating time, are not impacted by part design. Recoating is when an AM system spreads a new layer of powder before the build process can continue. Typical recoating time is in the range of 4–15 seconds per layer, depending on the specific machine configuration. Suppose a part is 100 mm (3.9 in) in height and the layer thickness is 50 µm (0.002 in). The part would consist of 2,000 layers, and the total recoating time would be 16,000 seconds (4.5 hours) if the recoating time is eight seconds per layer. Using an average machine time cost of \$65 per hour, the total cost of recoating time alone is about \$290. The only way to lower this cost is to reduce the build height, assuming layer thickness is constant.

Similar to recoating time, a machine's "purge" time is not affected by part design. This is the time to remove oxygen from the build chamber. Metal AM machines typically produce parts in an inert atmosphere, usually using argon, nitrogen, or a vacuum. The purge can take about 30–120 minutes, depending on the type of system. Some machines also preheat the build chamber and/or build plate, which also takes time. The recoating and purging times affect build time and cost, but they are largely independent of the part design.

The following table shows the main steps involved with metal AM and those in which the total build time is affected by the design of a part.

AM process step	Affected by design
Pre-processing	
Clean the AM system	no
Purge the system of oxygen	no
Preheat the AM system	no
Printing	
Spread layers of powder (recoating time)	no
Print contour lines	yes
Print interior hatch patterns	yes
Post-processing	
Remove build platform from machine	no
Recycle powder	no
Thermal stress relief	yes
Remove parts from build plate	no
Hot isostatic pressing	no
Remove support structures	yes
Heat treat	yes
Shot peen, machine surfaces, etc.	no
Inspect	no

Several design factors can reduce build time. The amount of powder that needs to be melted is the primary factor impacting time and cost of metal PBF. This can be affected through design practices. The operational principle of most metal AM systems is to melt the material in a serial fashion. A laser or electron beam scans across each layer to fuse the powder. The scanning path is referred to as contour lines at the part surface and hatching patterns in the part interior. The process is analogous to hand-drawing a solid circle with a pencil. First, the outer edge of the circle is drawn. The pencil is then moved back and forth many times to fill the circle. The larger the surface area, the longer it takes to create each layer of a part.

Suppose a hydraulic manifold was designed for conventional CNC machining. It may consist of a metal block into which many intersecting holes are drilled to form interconnected channels. These channels allow fluid to flow to the ports with valves and pressure sensors attached. The only way to machine internal connecting channels inside the block is to drill holes from the outside of the block. The holes are then plugged so that only the internal channels remain. If such a manifold was produced with AM, a layer would look similar to a filled square with a few holes in it. This is shown at the right in the following image.

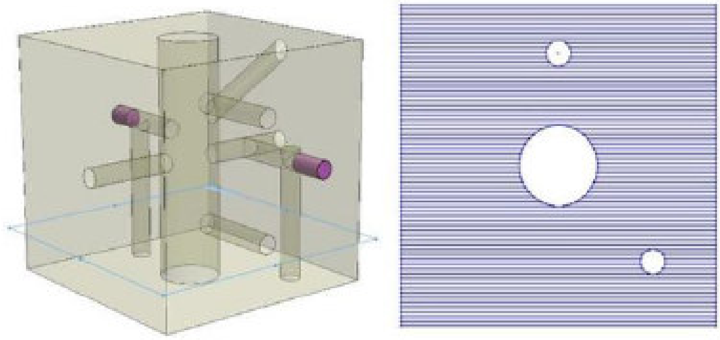


Fig. 181. Manifold designed for milling (left) and AM laser scan lines for one layer (right)

The crosshatch scanning pattern for the layers in this part requires a long scanning distance. If the manifold cross section measures 100 x 100 mm (3.9 x 3.9 in), and the hatch spacing is set to 0.1 mm (0.004 in), each square would require nearly 100 m (329 ft) of scanning. The beam must travel this distance to create one layer. As for cost, if the beam travels at 330 mm per second (13 in per second), it would take 300 seconds (five minutes) to solidify one layer of the part. In machine time, it would cost $5.41 for each of the 2,000 layers—a total of $10,820—which is an exorbitant cost. This part would also contain tremendous residual stress due to the thick sections.

In contrast, if the majority of the material is removed from the same part by shelling it to a specified wall thickness, the total scanning distance is greatly reduced, resulting in a significantly faster print time. If the shell thickness is set to 2 mm (0.079 in), and the same hatch spacing parameters as before are used, the total scan distance is about 4.5 m (14.8 ft)—a scan reduction of more than 95%. If the beam travels at 330 mm per second (13 in per second), it will take 13.6 seconds to hatch a part layer. This translates to $0.24 in machine cost per layer, which is a total machine cost of $487 for the 2,000 layers.

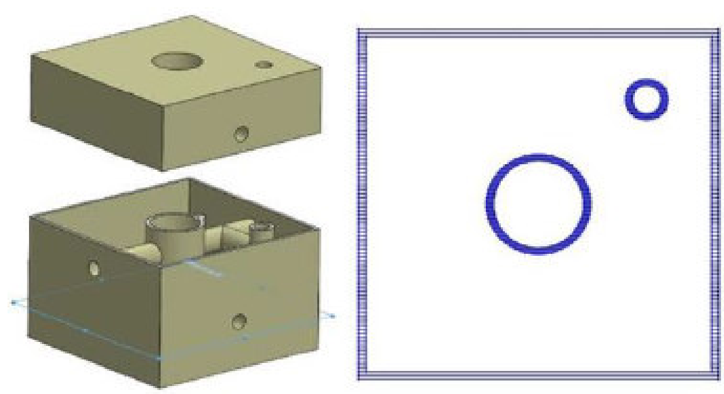


Fig. 182. Manifold shelled to reduce material consumption and machine time (left) and AM laser scan lines for one layer (right)

When the shelled part is finished, the internal cavities remain filled with unmelted powder. If weight or powder cost is a concern, openings can be added to provide access to remove the powder. Typically, the interior of the part would still contain some support material or lattice structures.

It is helpful to minimize large volumes of solid material when designing for AM since large masses of material usually offer little engineering value. They are likely to cause a part to warp and can induce residual stress. Also, they can greatly extend build times. Design techniques are available for eliminating large masses of material, including the shelling method just described. Another strategy is to fill solid regions with a lattice structure.

Avoiding large masses of material can also reduce the amount of thermal stress relief required. If a part has no large masses of material and a mostly regular wall thickness, it will contain less residual stress. Thus, heat treatment time can be reduced.

From a build-time perspective, it is best to produce a part in an orientation in which build height is minimized. This will result in the least number of layers and quickest build time. Build orientation also plays a role in the mechanical properties of a part, dimensional accuracy, surface finish, and required support material.

The following shows three versions of the block manifold: 1) conventionally machined and drilled, 2) adapted for AM, but with substantial support structures and excess material, and 3) fully optimized for AM. The third version can be built with minimal support material, as shown.

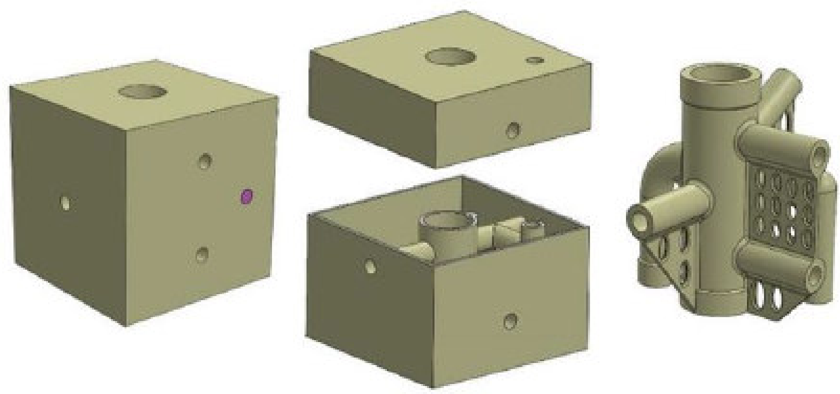


Fig. 183. Manifold for conventional manufacturing (left), adapted for AM (center), and designed for AM (right)

The following table shows the time and estimated cost of the three designs. It is impractical to produce the solid block design using AM.

	Solid block manifold	**Shelled block manifold**	**Fully optimized manifold**
Build time	191h 1m 33s	36h 31m 21s	19h 40m 39s
Service provider quote in 316L stainless steel	$15,294	$3,735	$1,986

Source: Wohlers Associates

This example illustrates the impact that machine time has on AM part cost. It is usually the most significant cost factor when using AM. It is possible to reduce time and cost significantly by avoiding large masses of material wherever possible. This shows that even a simple strategy of replacing large masses of material with an even wall thickness can have a substantial impact.

Further optimization by DfAM yields improved cost reduction. As with any form of manufacturing, AM production parts are only as good as the thought and testing put into the design. For companies that do not invest sufficiently in DfAM, the implications of cost and time can quickly compound.

DfAM strategies

Although DfAM includes specific tools and techniques, it is a new way of thinking. DfAM strategies are specific to AM and seek to add as much value as possible to the product. Broadly speaking, DfAM strategies are categorized as follows:

Lightweighting

This includes a range of methods to remove superfluous material from a part. Techniques include:

– *Shelling:* Hollow out a part to create a constant wall thickness. This is the technique used in one of the manifold examples in the previous section. For certain processes (e.g., vat photopolymerization (VPP), support material may remain trapped in the part.
– *Lattices:* Fill the interior of a part with a lattice structure or convert entire sections to lattices. Lattices are beam-based structures that resemble trusses. Lattices based on triply periodic minimal surfaces (TPMS), such as gyroids, are becoming popular for lightweighting. TPMS lattices are extremely efficient for heat dissipation because of their large surface area. They are also self-supporting.
– *Honeycombing:* Fill a part with a honeycomb structure as an alternative to lattices when the part experiences high fatigue loads. Filling a part with a gyroid structure can also work well for high-fatigue situations.
– *Topology optimization:* Remove material from within a design space based on a finite element analysis of the forces acting on the part. This results in a minimum amount of material needed to counteract those forces.
– *Generative design:* This involves the growing of material from fixed constraint points based on an FEA of the forces acting on the part. The result is a minimum amount of material needed to counteract those forces. Generative design, in contrast to TO, can create many potential design solutions.

Support minimization

This includes techniques used to reduce the amount of support material needed and to make it easier to remove. Some of these techniques include:

- *Changing the angle of overhanging features.* In general, part surfaces that are angled at less than 45° from horizontal require support. This requirement may vary by AM process. Wherever possible, part surfaces should be redesigned to have angles greater than 45° to avoid the need for supports.
- *Using permanent walls instead of supports.* Supports are often added in the form of temporary sacrificial walls. Consider replacing them with permanent walls that become features of the part, which are self-supporting.
- *Choosing the best profiles for horizontal holes.* Horizontal holes that have a diameter greater than about 8 mm (0.31 in) may require support. However, holes with teardrop, elliptical, and diamond profiles are self-supporting. Consider using them to replace circular profile holes.
- *Thinking about which surfaces are best for supports.* Due to ease of access, removing supports from the outside of a part is much easier than removing support from a cavity.
- *Changing the machine parameters.* This reduces the need for supports or the angle at which they are needed. In recent years, several system manufacturers have changed their machine parameters to reduce or eliminate the need for supports.

Minimizing residual stress and distortion

Use lightweighting techniques to minimize large masses of material. Large masses of material are the single biggest contributor to residual stress because they cool more slowly than thin features. Substantially reduce this problem using some of the lightweighting techniques described previously.

- *Avoid large downward-facing horizontal flat areas.* A sudden change in surface area between adjacent layers, such as that resulting from a large horizontal surface, can induce significant stress and distortion. Consider changing the part design to avoid large horizontal surfaces or use a different build orientation to change the build angle of these surfaces.
- *Designing to cope with anisotropy.* Certain AM processes build parts that are more anisotropic than others. This means their properties, such as tensile strength, are not the same in all directions. Give careful consideration to build orientation to avoid a negative impact on critical functional areas of the part.
- *Fillet all internal corners to minimize stress concentrations.* A sharp internal corner is a key point at which a stress concentration forms and where cracking of the part initiates. Filleting all internal corners, typically to a radius about 25% of the general wall thickness, is a simple technique to reduce this problem.

– *Simulate part distortion with FEA.* Software is available that can predict the distortion of a part. Based on this data, the computer-aided design (CAD) model can be "pre-distorted" in the opposite direction so that the resulting part has no distortion.

Improving surface finish

– *Carefully choose build orientation to enhance the most critical surfaces.* In general, the worst surface finishes are on downward-facing surfaces and those from which support material must be removed. The best surface finish is typically found on vertical or near-vertical surfaces. Also, the AM stair-step effect can be highly visible on gently curved and nearly horizontal surfaces. Carefully consider build orientation to avoid poor surface finish in the most critical areas.
– *Use textures to hide stair-step lines.* The use of a texture, such as a woven, leather, or stamped surface, can be a useful tool for camouflaging stair-step lines.
– *Include fixture points for mounting the part into the post-processing system.* Setting up a part for post-processing, such as CNC machining, can be time consuming. The part must be mounted precisely in the machine with the correct orientation and a means of accurately setting the machining origin. Designing mounting points into the AM part makes it easier to locate and orient on the post-processing system. This can save time and improve the post-processing outcome.
– *Choose the right surface for aesthetic enhancements.* Examples are logos and text. Differently angled surfaces on an AM part can result in different surface finishes. Carefully consider which surfaces might include text or logos. Choose a text font size to ensure legibility. If a logo or text is located on a specific surface, consider the surface's orientation before printing.
– *Use recessed rather than embossed text.* This makes post-processing easier. Adding logos, part numbers, and assembly instructions to parts can add value. If the part needs to be sanded, any protruding text is likely to be damaged or removed during the post-processing operation. An additional benefit of recessed text is a reduction in the amount of material used, resulting in a shorter build time.
– *Attach support material to surfaces that require the best surface finish.* These surfaces will need to be machined or post-processed anyway to give them the desired surface finish.
– *Change machine parameters to improve the part surface finish.* Surface finish can sometimes be improved by changing the hatch pattern, changing the energy density used on outer surfaces, or double-melting the outer surfaces of a part.

Part consolidation

Part consolidation involves minimizing the number of parts in an assembly by joining many simple parts into a smaller number of them. This reduces labor, assembly, inventory, and certification paperwork. It also reduces the number of manufacturing operations and materials used in a product.

- *Parts that do not move relative to one another and are made from the same material.* Consider joining them into a single part. If they are made of different materials, consider using the stronger material and consolidating them into a single part. The cost savings achieved using a simpler assembly may outweigh the use of a more expensive material.
- *More than one third of the parts are fasteners.* If this is the case, consider joining the parts to eliminate the need for fasteners.

Mass customization

Personalize products for customers. With AM, the cost of making different versions of a product may be similar to making all the parts identical. Consider making a custom product for each customer. This is used extensively in healthcare applications, such as prosthetics and implants.

Product performance improvements

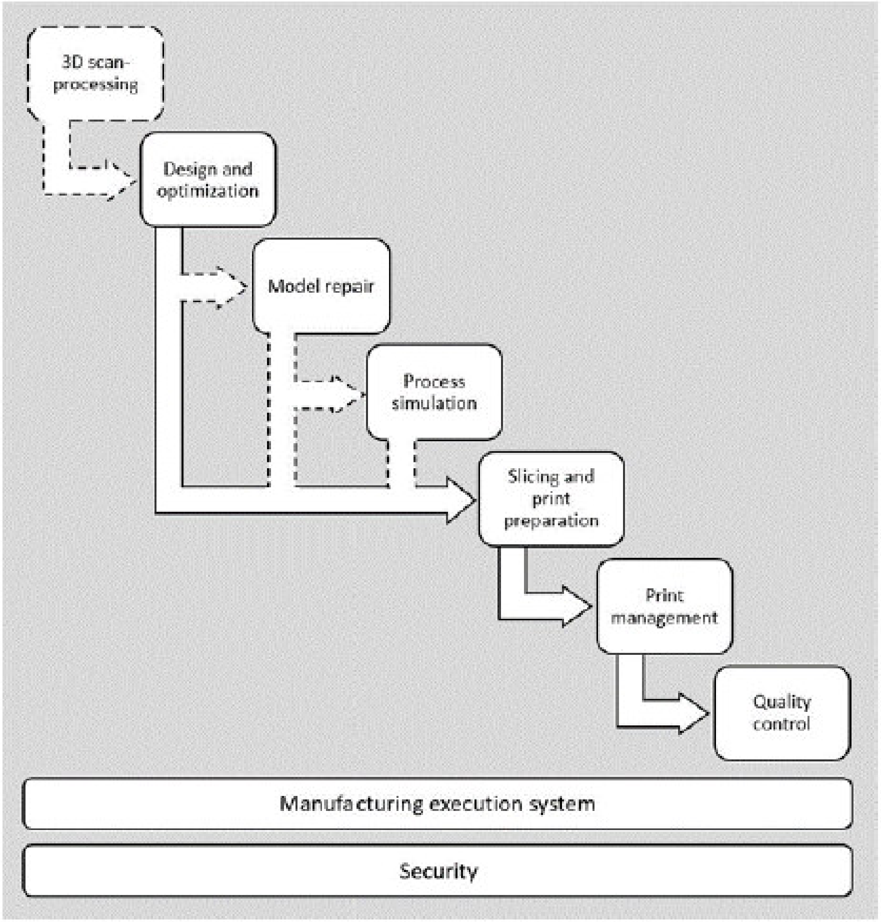
Exploit the strengths of AM. This includes certain techniques that are unique to AM, such as the use of conformal channels to improve part cooling. Shaping the part to optimize thermo-fluid mechanics or using gyroid structures can increase thermal efficiency. Consider geometrically controlled functionally graded materials. This involves varying the design to create regions with different properties. For example, design some areas to be rigid and others flexible within the same part.

Software

AM is a digitally driven technology. Digital models are created using CAD, 3D scanning, or another type of software tool. Software is critical in AM. It creates new design possibilities and enhances performance for a given workflow and application. Software is fundamental to DfAM and is key to creating organic designs and unusually complex structures.

The following diagram identifies areas in the process chain where software tools impact AM. The long boxes at the bottom represent software used throughout the workflow. The dotted box and arrows represent steps that may not be required in every instance. For example, process simulation software is often used only for metal parts. Print management and quality control apply to all workflows and can range from a simple visual inspection to sophisticated metrology equipment and software.

Fig. 184. AM software workflow. Source: Wohlers Associates



The tables in the following sections, while far from exhaustive, provide examples of the types of software products used to drive AM for final part production. Some products are multi-functional and are included in more than one table.

3D scan-processing software

by Michael Raphael

Some AM workflows use 3D scanning for final part inspection as one aspect of quality control. Other workflows begin with redesigning an existing part or product for which no CAD model exists. In these cases, reverse engineering with 3D scanning is used to capture the shape and geometric features of a physical part. The data is then imported into a CAD system for further modification.

The following table lists 3D scan-processing software products used for both reverse engineering and computer-aided inspection as part of quality control. Most of these products use point-cloud files from 3D scans as the input for subsequent processing. Point-cloud data is commonly generated by 3D scanning systems, so most software tools can import it.

Company	3D scan-processing	Computer-aided inspection
3Dflow www.3dflow.net	3DF Zephyr	–
3D Systems www.3dsystems.com	Geomagic Design X Geomagic Wrap Geomagic Sculpt Geomagic for SolidWorks D2P	Geomagic Control X
Agisoft www.agisoft.com	Metashape	–
Ansys www.spaceclaim.com	SpaceClaim	–
Artec www.artec3d.com	Artec Studio	–
Autodesk www.autodesk.com	Fusion 360 Meshmixer ReCap Pro	Fusion 360 PowerInspect
Bentley Systems www.bentley.com	Pointools ContextCapture	–
Capturing Reality www.capturingreality.com	Reality Capture RealityScan	–
Creaform www.creaform3d.com	VXmodel	VXinspect
Dassault Systèmes www.3ds.com	CATIA ICEM Surf	–
Evatronix www.evixscan3d.com	Evixscan3D	Evixmatic
FARO www.faro.com	Scene PointSense RevEng As-Built	CAM2 Measure CAM2 SmartInspect BuildIT
GOM www.gom.com	ATOS Professional	GOM Inspect
Hexagon www.hexagonmi.com	Leica Cyclone 3DR Leica Cyclone Leica CloudWorx REcreate	Spatial Analyzer PC-DMIS Quindos Inspire
InnovMetric www.innovmetric.com	PolyWorks Modeler PolyWorks Talisman	PolyWorks Inspector PolyWorks Reviewer DataLoop
KVS www.mesh2surface.com	QuickSurface Mesh2Surface for SolidWorks Mesh2Surface for Rhino3D	–
Materialise www.materialise.com	3-matic Mimics Magics	–
Matterport www.matterport.com	3D Content Platform	–
Lumafield www.lumafield.com	Voyager	
Metrologic Group	–	Metrolog

Company	3D scan-processing	Computer-aided inspection
www.metrologicgroup.com		
Nikon Metrology www.nikonmetrology.com	Focus Handheld	Focus Inspection
Occipital www.occipital.com	Skanect Canvas	
Polyga www.polyga.com	XTract3D Flex	–
PTC www.ptc.com	Creo Reverse Engineering Extension	–
ReconstructMe www.reconstructme.net	ReconstructMe	–
Reverse Engineering.com www.reverseengineering.com	HighRES Integrated Point Cloud Processor	–
RevWare www.revware.net	RevWorks	–
Riven www.riven.ai	Riven	–
Robert McNeel & Associates www.rhino3d.com	Rhino	–
Siemens www.siemens.com	Imageware	–
Smarttech3D www.smarttech3D.com	Smarttech3Dmeasure	Smarttech3Dmeasure
Trimble www.trimble.com	RealWorks	–
Verisurf www.verisurf.com	Verisurf	Verisurf
VirtualGrid www.vrmesh.com	VRMesh Studio VRMesh Reverse	VRMesh Survey
Volume Graphics www.volumegraphics.com	VGStudioMAX VGStudio	VGMetrology
Wenzel www.wenzelamerica.com	PointMaster	OpenDMIS Quartis Virtual CMM

Source: Direct Dimensions and Wohlers Associates

Topology optimization, generative design, and algorithmic modeling

Much of the DfAM is done using traditional CAD software. However, the geometric complexity offered by AM often requires specialized design tools. The following table lists software products for generative design, TO, and lattice formation. These products differ from traditional CAD, although some include 3D modeling capabilities.

TO, for example, is a physics-driven method in which the user sets up one or more load cases and design parameters. Using FEA, the software identifies and eliminates material elements that do not contribute to the function of a part.

Algorithmic modelling, which has increased in popularity over the past few years, uses algorithm-controlled workflows to automate the design process. Algorithmic modelling is particularly useful for generating complex conformal lattices or functionally graded TPMS structures, such as the complex gyroid structures used in heat exchangers.

Company	**Product/module**	**Application**
3D Systems/Oqton www.oqton.com	3DXpert	CAD design, TO, generative design, latticing, algorithmic modeling, and mesh repair
Altair www.altair.com	Inspire OptiStruct	Generative design and TO TO
Ansys www.ansys.com	Additive Suite	TO and lattice structures
Autodesk www.autodesk.com	Inventor Fusion 360 with Netfabb	CAD design and TO CAD design, TO, generative design, and latticing
Carbon www.carbon3d.com	Paramatters CogniCAD Design Engine	Generative design, TO, and simulation Latticing
Dassault Systèmes www.3ds.com	Catia Solidworks Tosca	CAD design and TO CAD design and TO TO
Desktop Metal www.desktopmetal.com	Live Parts	Generative design and TO
DTU www.topopt.mek.dtu.dk	TopOpt	TO
Synera www.synera.io	Synera (formerly Elise)	Algorithmic modeling, TO, and generative design
Gravity Sketch www.gravitysketch.com	Gravity Sketch	Virtual-reality-based modeling
General Lattice www.generallattice.com	Frontier	Lattice software application within Rhino
Gen3D www.gen3d.com	Sulis Flow Sulis Lattice	Algorithmic design Lattice design
Hexagon www.hexagon.com	MSC Apex	Generative design and TO
Hyperganic www.hyperganic.com	Hyperganic Core	Algorithmic modeling
nTopology www.ntopology.com	nTopology	Algorithmic modeling, generative design, and TO
PTC www.ptc.com	Creo	Generative design and TO
Parametric House www.parametrichouse.com	tOpos	TO plugin for Rhino
Robert McNeel & Associates www.rhino3d.com	Rhino + Grasshopper	CAD design and algorithmic modeling
Siemens www.sw.siemens.com	Solid Edge NX	CAD design, generative design, and TO CAD software with integrated TO, lattice structures, and support structure generation
TOffeeAM www.toffeeam.co.uk	TOffeeAM	Generative design software

Source: Wohlers Associates

Software tools for lattice, mesh, and cellular structures transform solid volumes of a 3D model into many small trusses. These structures reduce material and weight while maintaining sufficient load-bearing capabilities. This is usually accomplished by transferring the completed model from a traditional CAD system into specialized lattice-generating software. Conversely, the output from optimization software is often input to a traditional CAD system for additional work, such as surface smoothing.

Repair

Once a design is complete, a CAD model must be converted to a format suitable for the AM system. The STL file format has been the de facto AM standard since AM was first commercialized in the late 1980s. However, STL files are not always created properly due to flaws in the software or errors by inexperienced users. The products in the following table are used to repair 3D models. These software tools repair, manipulate, emboss text, combine models, and offer other functionality to help prepare models for 3D printing.

Company	Product/module	Application
3D-Tool www.3d-tool.com	3D-Tool CAD-Viewer	STL file viewing and checking
Autodesk www.autodesk.com	Meshmixer Fusion 360 with Netfabb	STL repair and lattices Mesh repair, nesting, and print preparation
Ansys www.ansys.com	SpaceClaim	Mesh repair and print preparation
CADspan www.cadspan.com	CADspan	Mesh repair
DeskArtes www.deskartes.com	3Data Expert	Mesh repair, nesting, and print preparation
Fixie www.fixie3d.com	Fixie	Mesh repair and print preparation
Materialise www.materialise.com	Magics	Mesh repair, nesting, and print preparation
MeshLab www.meshlab.net	MeshLab	Mesh editing
Microsoft www.microsoft.com	3D Builder	Mesh editing
Polygonica www.polygonica.com	Polygonica	Mesh editing

Source: Wohlers Associates

Simulation

Simulation software is designed to predict distortions during a build. It assists in preventing distortion-based build failures, particularly for metal PBF. Like TO and FEA, the software relies on physics-based mathematics to predict stress and distortions. Such predictions help prevent critical build failures by identifying problems in advance.

Some software products compensate for distortion to produce accurate dimensions of the final part compared to the original model. Simulations may require extensive computer processing power and are often not practical to run for every build. This software can improve speed and quality, so its use will likely become standard practice when designing for AM.

Company	Product/module	Application
3D Systems www.oqton.com	3DXpert Amphyon	AM simulation and print preparation Simulation-based process-preparation software for metal PBF
AdditiveLab www.additive-lab.com	AdditiveLab RESEARCH	Metal AM simulation
AlphaSTAR www.alphastarcorp.com	Genoa 3DP	Design and build simulation for polymers, metals, and ceramics
Altair www.altair.com	Inspire Print3D	Simulation-based process-preparation software for metal PBF
Ansys www.ansys.com	Additive Print	Support structure optimization, simulation, and print preparation for metal AM
Autodesk www.autodesk.com	Fusion 360 with Netfabb	Simulation for metal PBF
Comsol www.comsol.com	Comsol Multiphysics	AM simulation
Dassault Systèmes www.3ds.com	Simulia	AM build simulation
Desktop Metal www.desktopmetal.com	Live Sinter	Metal AM simulation for sintered parts
Flow-3D www.flow3d.com	Flow-3D AM	Laser PBF AM simulation
Hexagon www.hexagon.com	Digimat Simufact Additive	Material simulation tool AM simulation and AM preparation
Materialise www.materialise.com	Magics	Data preparation and STL editing with Simufact simulation module available
nTopology www.ntopology.com	nTopology	Simulation and AM preparation
Siemens www.sw.siemens.com	Solid Edge NX	AM simulation AM simulation
SimScale www.simscale.com	Simscale	Cloud-based AM simulation

Source: Wohlers Associates

Slicing and print preparation

Once a 3D model is ready to print, slicing and print preparation software converts the model into data the AM system reads. These software tools are presented in the following table. They are sometimes referred to as slicers because they slice the 3D model into thin cross sections that represent the layers of the part.

Other features of these software tools may include 2D and 3D nesting, support generation, and print visualization. Many industrial and desktop 3D printers bundle system-specific software that includes these capabilities. Machines from Markforged can read files from Eiger only, but many desktop 3D printers can use open-source software such as Cura or GrabCAD Print.

Company	Product/module	Application
3D Systems www.3dsystems.com	3DXpert	Design optimization and print preparation for polymer and metal AM
Ai Build www.ai-build.com	AiSync	Toolpath generation for multi-axis AM systems
AstroPrint www.astroprint.com	AstroPrint	Cloud-based slicing
Autodesk www.autodesk.com	Fusion 360 with Netfabb	Slicing and print preparation
CoreTechnologie www.coretechnologie.com	4D_Additive	Build preparation and support generation
Craftbot www.craftbot.com	Craftware Pro	Slicing and 3D printer hosting
Create it REAL www.createitreal.com	REALvision Pro REALvision Online	Slicing Slicing
Dyndrite www.dyndrite.com	LPBF Materials & Process Development	Build preparation
EOS www.eos.info	EOSPRINT 2	AM build preparation
gCodeViewer https://gcode.ws/	gCodeViewer	Online G-code visualizer, viewer, and analyzer
KISSlicer www.kisslicer.com	KISSlicer	Slicing
Markforged www.markforged.com	Eiger Fleet	Cloud-based build preparation, slicing, and print management
Materialise www.materialise.com	Magics Support Generation	Data preparation and STL editor with multiple modules available Automatic support material generation
OctoPrint www.octoprint.org	OctoPrint	Slicing
Prusa Research www.prusa3d.com	PrusaSlicer	Repairing, modifying, slicing, and 3D printer hosting
Raise3D www.raise3d.com	ideaMaker	Slicing
Repetier www.repetier.com	Repetier	Slicing and 3D printer hosting
ReplicatorG www.replicat.org	ReplicatorG	Slicing
Roboze www.roboze.com	Prometheus	Slicer
Simplify3D www.simplify3d.com	Simplify3D	Checking, previewing, repairing, and preparing files for 3D printing
Slic3r www.slic3r.org	Slic3r	Slicing
Stratasys www.grabcad.com	GrabCAD Print	Build preparation and slicing

Company	Product/module	Application
Ultimaker www.ultimaker.com	Cura	Slicing and 3D printer hosting

Source: Wohlers Associates

Print management

Once a 3D model is sliced, it is sent to an AM machine. Print management tools, such as those in the following table, oversee the printing process. Sometimes print preparation and management software is packaged into a single product. In other cases, the print management software is bundled with the AM system. Open-source software is also available, particularly for low-cost desktop systems. With some of these tools, users can start, queue, and track jobs remotely.

Company	Product/module	Application
3D Printer OS www.3dprinteros.com	3DPrinterOS	Cloud-based printer management
AstroPrint www.astroprint.com	AstroPrint	Cloud-based printer management
EOS www.eos.info	EOSCONNECT	Production management
Markforged www.markforged.com	Eiger Fleet	Cloud-based printer management
OctoPrint www.octoprint.org	OctoPrint	Network 3D printer hosting
Printrun www.pronterface.com	Printrun	3D printer hosting software, slicing, and print controller
Raise3D www.raise3d.com	RaiseCloud	Cloud-based printer management
Stratasys www.grabcad.com	GrabCAD Control	Printer management

Source: Wohlers Associates

Manufacturing execution systems

Manufacturing execution system (MES) software is becoming more popular among companies that operate many AM machines for production. MES tools track, monitor, and control manufacturing processes. Some of the systems manage the quotation of jobs and consider AM capacity and materials at multiple locations.

Company	Product/module	Application
3D Systems www.oqton.com	Oqton AM	MES
3DTRUST www.3dtrust.de	Additive MES	MES
3YOURMIND www.3yourmind.com	3YOURMIND	MES

Company	Product/module	Application
AMFG www.amfg.ai	AMFG	MES
AM-FLOW www.am-flow.com	AM-FLOW	MES
Authentise www.authentise.com	Authentise MES	MES
DNA.am www.dna.am	DNAam	MES
Fabpilot www.fabpilot.com	Fabpilot	AM value chain support
Link3D www.link3d.co	Link3D	MES
MakerOS www.makeros.com	MakerOS	MES
Materialise www.materialise.com	CO-AM	MES
Paperless Parts www.paperlessparts.com	Paperless Parts	MES

Source: Wohlers Associates

A service provider or contract manufacturer that operates several PBF systems may process thousands of parts per day for different customers. Managing and tracking these parts through printing and post-processing can be tedious. If not managed well, parts can be lost, fall out of spec, or be delivered to the wrong customer. MES software is an especially powerful tool when producing parts for end-use products.

Security

Security has become a difficult but necessary issue to address. Daily, terabytes of data flow between designers, machinists, clients, and other stakeholders, often by unsecured connections. With AM, digital data is transformed into physical objects. Corrupted data could lead to a catastrophic failure. Creative approaches are being developed to securely produce and maintain designs and AM parts, as shown in the following table.

Company	Product/module	Application
Alitheon www.alitheon.com	FeaturePrint	3D print security using machine vision
Identify3D www.identify3d.com	Protect	Security
Pirat.io www.pirat.io	Pirat.io	Anti-piracy service
Vistory www.vistory.com	MainChain	Blockchain security system

Source: Wohlers Associates

Medical image processing

by Andy Christensen and Nicole Wake

Patient-specific medical devices and anatomical models almost always originate from radiological imaging data. Medical image processing software is used to translate from radiology file formats—most commonly Digital Imaging and Communications in Medicine (DICOM)—to AM file formats. While theoretically, any volumetric radiological imaging dataset could be used to create these devices and models, the highest quality medical image data is required.

Computed tomography (CT) is the usual method for imaging bone structures and contrast-enhanced vasculature due to the relative ease of image post-processing. In-office cone-beam computed tomography (CBCT) has become popular in the dental field and for oral and maxillofacial surgeries. Another popular imaging technique is magnetic resonance imaging (MRI). It is used to create anatomical models. MRI is less useful for bone imaging, but highlights soft tissue, such as solid organs and cancerous lesions.

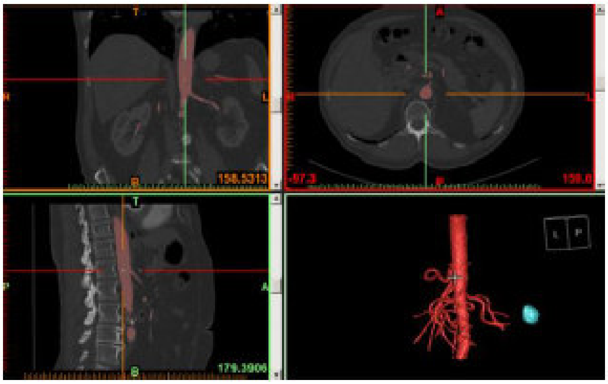


Fig. 185. Image segmentation from a CT scan of an abdominal aorta and branch vessels performed with Materialise Mimics software, courtesy of Nicole Wake

CT uses many X-ray projections to computationally construct a 3D image. A narrow X-ray beam passes through the subject and projects onto an opposing detector, similar to traditional 2D X-ray imaging. The X-ray source and detector rotate around a stationary subject and acquire images from many angles to create a cross-sectional image. The image of the cross section is then computed from these projections in a post-processing step. Only one contrast mechanism is used with CT because the signal intensity is linearly proportional to the tissue density. CT is the method of choice for bone imaging and is typically used to produce medical models of hard tissue structures.

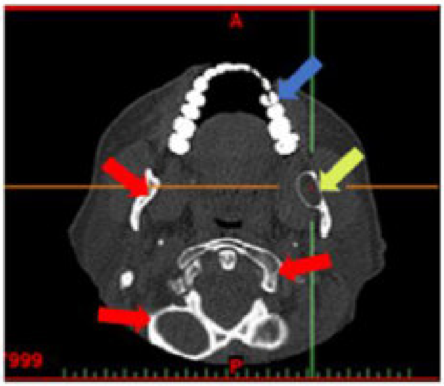


Fig. 186. CT image of a mandible with bone (red arrows), teeth (blue arrow), and tumor (yellow arrow), courtesy of Nicole Wake

CBCT operates on the same principle as traditional CT. However, instead of a single, thin X-ray beam making one revolution per image slice, a large, diverging X-ray beam (a cone beam) is paired with a large 2D detector array. In this way, CBCT makes possible the acquisition of a single image dataset from one revolution of the source-detector pair. Benefits include simplified logistics, ease of scanning, and reduced radiation exposure. However, increasing the span of the beam degrades contrast resolution, making segmentation somewhat difficult. Nevertheless, CBCT is very common for clinical use, particularly in dental specialties, oral and maxillofacial surgery, and ear, nose, and throat clinics. The ease of installation in a clinical setting and a relatively low price point makes it an attractive option. It is also used for patient alignment tasks in radiation therapy and image-guided surgery.

Recent advancements in CT include dual-energy (spectral) CT and photon-counting CT. Dual-energy CT is a technique that uses two separate X-ray photon energy spectra. This supports the investigation of materials that have different attenuation properties at varying energy levels. Photon-counting CT uses recently developed energy-resolving X-ray detectors, which count the number of incoming photons and measure photon energy. This method results in improved image resolution, reduced radiation exposure, and a reduction of artifacts. Also, photon-counting CT creates new opportunities for quantitative imaging compared to conventional CT technologies.

MRI is based on the principle of nuclear magnetic resonance and employs strong magnetic fields and radio waves. Hydrogen protons in water molecules become aligned in a strong primary magnetic field. Radio waves at a specific frequency are introduced to perturb protons from their alignment within the magnetic field. The frequency can be calculated from the strength of the magnetic field. When the radio waves are removed, protons return to their alignment within the magnetic field at different rates and emit a measurable echo signal. The rate of return depends on the surrounding molecules (i.e., tissue type). The echo signal is used to determine relaxation times, which is the time required for hydrogen nuclei to return to their alignment in the magnetic field. Local relaxation times are used to reconstruct cross-sectional images.

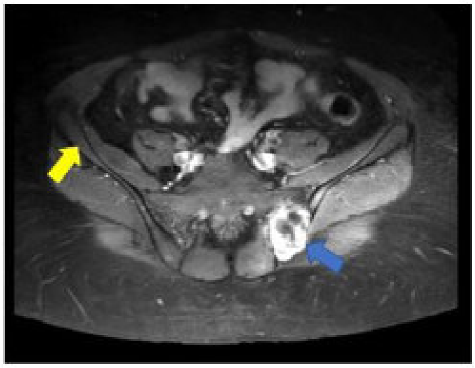


Fig. 187. MRI image showing the same pelvis cross section as previous illustration; bone (yellow arrow) is less visible, but the tumor (blue arrow) is better defined, courtesy of Nicole Wake

Most imaging technologies used for medical modeling produce data in serial section format in the form of 2D images. These images represent a finite thickness, with data taken at increments along the axis of an object being scanned. The 2D images, stacked at the associated thickness increments, form a 3D volume. For example, a CT scan may be taken using slice thicknesses of 1 mm (0.04 in). In this case, an object that is 20 mm (0.79 in) in length would have 20 slices. Within these 20 slices, data is available for the entire object being scanned. However, image-processing tools are needed to "extract" the areas of interest, such as bone structure or a tumor. In-plane resolution for most medical imaging studies of all types can be 0.1–1.0 mm (0.004–0.04 in).

Once a dataset has been acquired, the images are typically stored in a hospital or clinic picture archive and communication system (PACS). The most common format found today for medical imaging is the open-source standard DICOM. Working Group 17 of the DICOM Standards Committee has worked to support storage and encapsulation needs for 3D printing file formats, including STL and OBJ.

Specialized software is needed to efficiently and accurately handle medical image data to read the DICOM format and to support image processing. Exporting this medical image data to a suitable AM format is also crucial to workflow accuracy. Primary tasks in medical image processing for AM include 1) import of native medical images, 2) image segmentation, 3) slice/volume editing, and 4) STL file generation. The following chart shows some of the major steps in producing anatomical models.

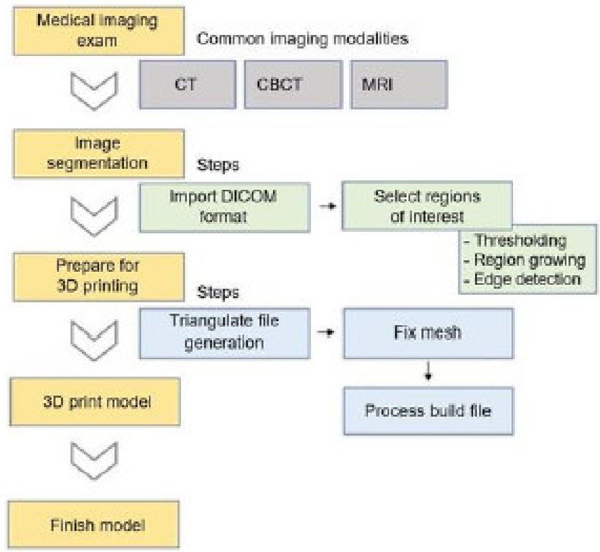


Fig. 188. Overview of the process of using medical imaging data to produce a 3D-printed anatomical model, courtesy of Nicole Wake

The U.S. Food and Drug Administration (FDA) has been active in the last decade regarding the regulatory landscape for medical devices made by AM. An initial FDA public workshop in 2014 attracted more than 500 industry attendees. The FDA published a draft guidance document in 2016 entitled Technical Considerations for Additive Manufactured Medical Devices. It outlines the administration's collective thinking on the topic. The draft technical guidance was made final in December 2017. It is a formal reference from a regulatory and quality assurance standpoint. Medical device manufacturers consult it when working on a 3D-printed medical device. The FDA has reportedly cleared more than 250 AM medical devices as of September 2022.

The Radiological Society of North America launched its 3D Printing Special Interest Group (SIG) in 2016. It marked a significant point for the technology and its use in clinical care. The group reached several important milestones in its first three years. It published the first clinical consensus guidelines document, a comprehensive review and vetting of clinical diagnoses and indications for 3D printing. The SIG collaborated with the FDA to hold a joint meeting in August 2017. Also, a collaboration occurred with the American College of Radiology (ACR) on establishing new Category III CPT codes for anatomical models and guides. This led to the creation of a first-of-its-kind Anatomic Model Registry.

In December 2021, the FDA released a white paper titled 3D Printing Medical Devices at the Point of Care. The stated purpose is to solicit opinions from relevant stakeholders. The paper does not represent FDA policy but provides the organization's viewpoints surrounding the topic. The paper highlights three main scenarios for the 3D printing of medical devices at the point of care, including the following:

- Healthcare facility using a cleared medical device production system
- Traditional medical device manufacturer co-located at or near the healthcare facility
- Healthcare facility assuming all responsibilities of traditional medical device manufacturer

This is a refinement of the previously presented Conceptual Framework the FDA began discussing in 2019. The FDA seeks feedback on what it is calling "very low-risk devices," which may fall outside of its scope. The concept of risk is discussed throughout the FDA document, as are the varying levels for healthcare facilities, capabilities, and controls. Resolving these issues may be key to determining what devices are considered "very low risk."

The following table lists some of the medical image processing software products that have received FDA clearance. These products can be used to produce 3D-printed anatomical models for diagnostic use.

Product	Company	Website
Bonelogic	Paragon 28	www.disior.com
Customize	3D-SIDE	www.3d-side.com/applications
D2P	3D Systems	www.oqton.com/d2p
ImmersiveView Surgical Plan	ImmersiveTouch	www.immersivetouch.com/immersiveview-surgical-plan
Mimics inPrint	Materialise	www.materialise.com/en/healthcare/mimics-inprint
Mimics	Materialise	www.materialise.com/en/healthcare/mimics-innovation-suite/mimics
Ricoh 3D for Healthcare	Ricoh	www.ricoh-usa.com/en/industries/healthcare/3d-printing-for-healthcare
Simpleware Scan IP Medical	Synopsys	www.synopsys.com/simpleware/software/scanip.html

Source: Andy Christensen, Nicole Wake, and Wohlers Associates

The following table lists medical image processing software products that have not received FDA clearance. These products may be used for research and other purposes.

Product	Company	Website
3D-Doctor	Able Software Corp.	www.ablesw.com/3d-doctor/3ddoctor.html
Advantage Workstation	GE Healthcare	www.gehealthcare.com/education/advantage-workstation-for-diagnostic-imaging
Amira	Thermo Fisher Scientific	www.fei.com/software/amira-3d-for-life-sciences
AVIEW Modeler	Coreline Soft	www.corelinesoft.com/en
AW	GE	www.gehealthcare.com/products/advanced-visualization
Dolphin 3D Surgery	Patterson Dental	www.dolphinimaging.com
F.A.S.T.	Fovia	www.fovia.com
IntelliSpace Portal	Philips	www.usa.philips.com/healthcare/product/HC881102/intellispace-portal-10-advanced-visualization
iNtuition	TeraRecon	www.terarecon.com
Medical Design Studio	Anatomage	www.anatomage.com/medical-design-studio
OsiriX MD	Pixmeo	www.osirix-viewer.com
Simpleware ScanIP Medical	Synopsys	www.synopsys.com/simpleware.html

Product	Company	Website
Synapse 3D	Fuji	healthcaresolutions-us.fujifilm.com/enterprise-imaging/synapse-3d
syngo.via Frontier	Siemens	www.siemens-healthineers.com/en-us/medical-imaging-it/syngo-carbon-products/frontier
Visage 7	Visage Imaging	www.visageimaging.com/visage-7
Vitrea	Canon	www.vitalimages.com/3d-printing

Source: Andy Christensen, Nicole Wake, and Wohlers Associates

Process monitoring of metal powder bed fusion

by Luke Scime

Quality assurance (QA) is necessary to provide confidence for metal PBF serial production. Most conventional manufacturing processes competing with PBF are highly controlled and monitored to provide this level of confidence. In-situ process monitoring is one way to reach a level of QA that meets industry standards.

Category 1 – Subsystem calibrations: AM system calibrations are necessary for process monitoring. These calibrations may or may not be captured in the machine log files. Monitoring uncalibrated sensors adds risk to the process outcome and typically violates a quality management system.

Subsystem calibrations include, but are not limited to laser power, laser caustic, laser focus, *x-y* spatial calibration, and laser scan speed. They also include sensors for oxygen, humidity, temperature, feedstock, and process monitoring, as well as *z* axis control, process gas flow, cooling water flow, and recoater motor torque. The calibrations should be performed in the usual operational use range. It makes no sense to use 20.95%, for example, as a calibration point for an oxygen sensor when the process monitoring is typically in the parts per million (PPM) range.

Category 2 – Systemic monitoring: Except for process monitoring sensors, this category is the real-time collection of machine sensor data calibrated in Category 1. The data recording needs to be at a frequency supporting the process being monitored. For example, oxygen sensors need to record at a frequency that can detect oxygen spikes should a valve fail to function properly.

Category 3 – Static imaging: Static imaging uses sensors to check for powder bed disturbances and detect contamination on the laser window surface. They are typically complementary metal oxide semiconductor (CMOS) cameras but can also be structured light scanners. Some types of machine learning compare the surfaces to a known value, checking for deviations. Illumination of the surfaces is paramount in ensuring repeatability.

Category 4 – Video data analysis: Savvy laser PBF machine operators with more than 1,000 hours of observing the process through the AM system window (face-to-glass) are capable of discerning when a process is not optimal. The condensate plume coming from the laser-to-powder interaction changes in a subtle way. Camera data can help automate this process to quantify the condensate plume and to map the fall location of larger spatter particles ejected from the melt pool.

Category 5 – Melt pool monitoring (MPM): MPM is also known as in-situ monitoring. This category includes both on- and off-axis observation of different wavelengths of light emitted from the beam and powder interaction. The end goal is to measure the size and temperature of the melt pool and detect indications outside the normal range.

Category 6 – Subsurface monitoring: The downside of Category 5 detection is that with the laser PBF process using optimized parameters, the consolidated material is typically remelted—often twice—as the laser passes across the same consolidated area on the next layers. Material discontinuities are often healed during these subsequent melt events. In-situ nondestructive evaluation (NDE) is ideal and avoids the need for ex-situ NDE, such as ultrasonic inspection.

The relative complexity and novelty of metal PBF presents challenges for implementing traditional QA programs. These same unique characteristics also present opportunities for revolutionizing the QA paradigm by supporting the production of "born-qualified" parts. The born-qualified approach is a major shift from traditional QA, which relies on performance statistics collected from a large volume of nominally identical parts. Born qualified controls process parameters to ensure parts are produced consistently and with minimal variability.

The traditional approach to QA depends on a historical understanding of long-established methods of manufacturing. The layer-wise nature of PBF permits observation of the internal volume of parts as they are produced. The ASTM E07 Committee on Nondestructive Evaluation approved F1316, which defines an important terminology distinction between flaws and defects.

A flaw is an imperfection or discontinuity (in the consolidated material) caused by a process anomaly that may be detectible by nondestructive testing and is not necessarily a rejectable part. A defect occurs when one or more flaws whose aggregate size, shape, orientation, location, or properties do not meet specified acceptance criteria, making a part rejectable. Therefore, a part can contain flaws, but have zero defects. The implication here is that process monitoring and control should be implemented in order to resolve flaws. Machine learning routines can evaluate defects based on the acceptance criteria for the classification of part in production.

Other challenges of metal PBF relate to the size and timescales over which the processes operate. For example, detection of relevant porosity may require collecting data with a spatial resolution in the order of 10 µm (0.0004 in). This must be achieved for an entire build consisting of thousands of kilometers of melt pool travel. Similarly, with high cooling rates, melt-pool-scale dynamics occur in tens or hundreds of microseconds. Data are typically recorded at rates above

10 kHz. For builds that process for one week or longer, this approach quickly becomes a substantial burden of data transmission, processing, and storage.

The aim of the born qualified approach is to achieve a generalized framework for approving low-production-volume AM parts with minimal reliance on expensive ex-situ characterization. This requires a series of algorithms and models to process and correlate in-situ data collected during the printing process. This framework integrates data across different scales and facilitates machine training or deep-learning-driven transfer functions. The first stages consist of traditional signal processing and computer vision algorithms. They are used to enhance, spatially map, co-register, and fuse the raw, multi-modal sensor data.

The next intermediate stage is generally dedicated to anomaly and flaw detection at a relatively high resolution. This can be achieved using deep-learning-driven image analysis. Once the flaw locations are identified, they can be included in a lower spatial resolution machine learning model. This model is trained to predict local material properties of interest. At this scale, low-resolution temporal data, thermal modeling, microstructural modeling, and post-processing operation data can be included. Also included are local part geometries and process metadata. Finally, the predicted localized material properties can be loaded into traditional, physics-based finite element models. They are used to predict the performance of a part in a specific application under a particular loading condition.

Sensing techniques for PBF process monitoring generally fall into on-axis or off-axis sensing. On-axis sensors are primarily applicable for laser-based processes and "track" the melt pool throughout the entire build. Typically, these sensors image the vapor plume light emissions just above the melt pool. They can indicate melt pool size, stability, morphology, temperature, and composition. The sensors must collect data at high rates (around 10 kHz) to capture the relevant dynamics and produce results with the required spatial resolution. The most common on-axis sensors are photodiodes of one- or two-color pyrometers, thermal imagers, visible-light imagers, and spectrometers.

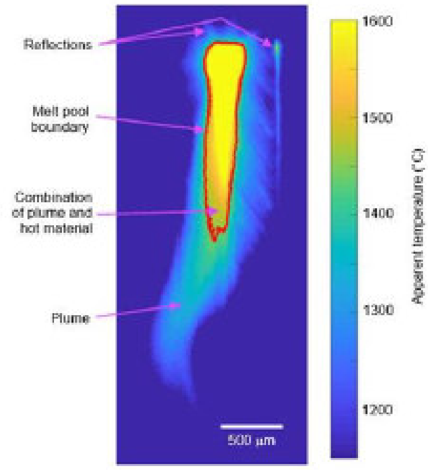


Fig. 189. High-speed visible-light melt pool image, courtesy of Brian Fisher and Carnegie Mellon University

Off-axis sensors do not pass through the laser optics. They have either a field of view covering the entire print area or a separate scanning mechanism to scan the powder bed. Typically, such sensors produce one or more "images" of the print area after each layer is printed. Common data capture modalities include imaging after fusion of the layer, imaging after spreading of the layer, and imaging during the layer fusion itself. These sensors are often designed to detect part-scale cooling rates, powder spreading issues, part distortion, ejecta from the melt pool, dimensional tolerance deviations, and machine stability issues.

The most common off-axis sensors include visible-light imagers, infrared or near-infrared imagers, integrated or long-exposure infrared imagers, and structured light topology measurements. Others include profilometry measurements (either with a laser or a mechanical probe), high-resolution line scanners, and backscatter or secondary electron detection for electron beam PBF.

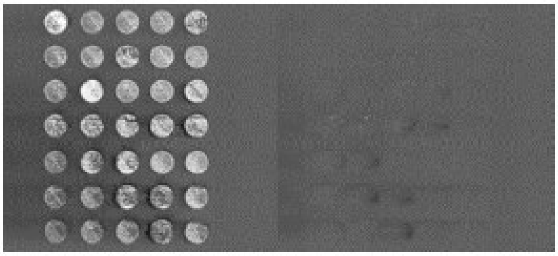


Fig. 190. Visible light images captured immediately after layer fusion (left) and powder spreading (right) on a laser PBF system, courtesy of the Manufacturing Demonstration Facility at Oak Ridge National Laboratory

Off-axis sensors that record time series data at very high frequencies share characteristics with both on- and off-axis techniques. Such modalities include passive acoustic sensors and infrared photodiodes with fields of view covering the entire build area. By synchronizing the data with the laser beam location, the time-resolved information can be mapped spatially. Often, resolutions approach or exceed that of on-axis sensors.

Many commercial machines generate log files containing basic information about machine performance. Recorded data includes build plate temperature, shield gas flow rates, chamber pressure, oxygen concentration, and actuator current draw. While the data acquisition frequency varies widely between manufacturers, it can be used to identify anomalous processing conditions that may cause part or layer flaws. This data can also be mapped spatially if it is collected at sufficiently high frequency with scan-path information.

Several promising non-commercialized sensing modalities are currently under development. These techniques focus on detection of small subsurface pores as this goal remains challenging for current commercial technologies. These sensing modalities include on-axis optical coherence tomography, surface acoustic waves, active ultrasonic transducers, and Schlieren imaging of the vapor plume. High-speed X-ray melt pool radiography is a useful tool for understanding process dynamics. However, the high photon flux restricts this technique to only the largest X-ray sources, making it non-viable for production-scale process monitoring.

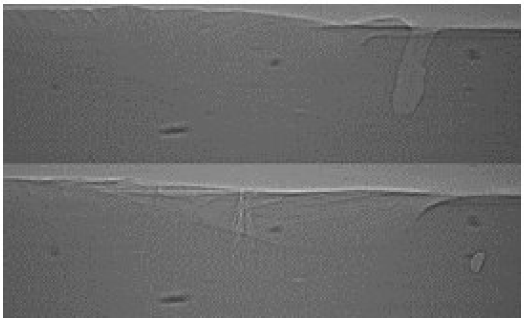


Fig. 191. High-speed X-ray melt pool radiography images with keyhole vapor cavity (top) and solidification cracking (bottom), courtesy of Carnegie Mellon University and Argonne National Laboratory

Collecting in-situ process data is only part of the challenge. Typically, substantial data processing is required to correlate the data with relevant part quality metrics. Such algorithms include data reduction and compression techniques, computer vision analyzes, data registration and synchronization, and transformations between the frequency and time domains. Machine learning and deep learning algorithms are being used to detect defects and anomalies in both spatial and temporal data.

For QA, it is insufficient to merely collect the data. The correlations between the in-situ data and the part's properties must also be understood. Currently, the AM community approaches this challenge by using statistical and machine learning models. Due to the high data dimensionality and the complexity of the manufacturing processes, such models generally require a large amount of data for "training."

While collecting enough in-situ data can be difficult, it is typically the collection of the corresponding ex-situ measurements that proves to be the bottleneck. Gray box and relay-based models are being developed that combine machine learning with physics-based modeling (e.g., thermal simulations) and engineering assumptions. They are expected to reduce the amount of training data required. Algorithm development should also prioritize machine, material, and geometric independence. This will increase the likelihood that solutions with high development costs can be scaled and broadly applied across the industry.

PBF machine manufacturers are increasingly recognizing the importance and added value of in-situ process monitoring. Most manufacturers include one or more sensing systems on their commercial AM systems. In general, commercial development of powerful data analysis and data fusion algorithms lags commercial sensor deployment. However, such efforts increased significantly in 2022.

A representative list of commercially available sensing systems has been compiled by Wohlers Associates, in alphabetical order. Significant activity in this space means that new companies and solutions are continually entering the market, so the list may not be exhaustive.

Aconity3D

The company focuses on open-architecture laser PBF systems. Its systems are highly configurable, and most support both on-axis photodiodes and on-axis high-speed cameras for process monitoring. Its printers can also include a visible-light camera, which takes images of the powder bed after each layer. Machine sensor data is accessible by the AconitySTUDIO control software.

Addiguru

Addiguru is a relatively new company offering third-party process monitoring solutions for laser PBF systems. The company's system consists of a visible-light camera that captures images of the powder bed. These images are then processed with a machine learning algorithm that flags flaws such as recoater-to-part impacts.

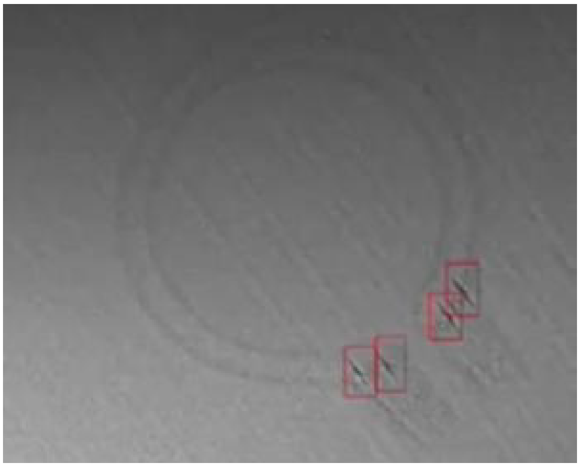


Fig. 192. Visible-light image from powder bed with highlighted flaws, courtesy of Addiguru

AddUp

AddUp's FormUp 350 printer logs printer health, oxygen concentration within the build chamber, and information regarding the shield gas flow. It also logs temperatures and the load on the powder recoating mechanism. Each printer includes a visible-light camera that captures an image of the powder bed immediately after layer fusion and after powder spreading. A microbolometer (thermal imager) captures a single image of the powder bed after layer fusion. A recent collaboration between AddUp and Interspectral will develop new data visualizations, anomaly detection capabilities, and augmented reality tools. These will be used with AddUp's upcoming melt pool sensing system.

EOS

EOS's sensing capabilities are integrated into the EOSTATE Monitoring software suite. EOSTATE Base tracks printer health and process parameters. It monitors oxygen concentration within the build chamber, the status of the shielding gas filtration system, and build-plate temperature. EOSTATE PowderBed captures visible-light images of the powder bed immediately after layer fusion and after powder spreading. Currently, EOSTATE PowderBed is primarily a documentation feature, although EOS and its partner Zeiss are developing algorithms to automate analysis of these layer images.

EOSTATE MeltPool uses one on-axis photodiode and one off-axis photodiode to collect light emitted from the melt pool, vapor plume, and the surrounding region. These data streams have a high temporal and spatial resolution and can provide useful insight into off-nominal laser or melting conditions. EOSTATE Exposure OT images the entire build area using an off-axis near-infrared camera during layer fusion. By capturing data at a moderately high frame rate, a single composite image can be constructed for each layer. This image contains information related to emitted light intensity across the layer and can be used to observe spatter, hot spots, and cold spots.

GE Additive

GE Additive's laser PBF systems are equipped with varying process monitoring capabilities. Its M2 products log machine health data, information about the shielding gas flow, oxygen concentration within the build chamber, and build-plate temperature. The latest M2 models are equipped with a series of quality management modules. The QM Coating module, for example, captures visible-light images of the powder bed immediately after layer fusion and after powder spreading. These images are primarily used for documentation. However, they can also be analyzed under certain conditions to detect powder short feeds and automatically adjust the powder dosing factor.

The QM Meltpool module consists of an on-axis high-speed camera and an on-axis photodiode. The module captures emitted and reflected light from the melt pool region. This data is spatially mapped for visualization purposes. The QM Coating and QM Meltpool modules are generally not available on the large-format X Line systems.

GE Additive's electron beam PBF systems are equipped with extensive machine health logging capabilities. Hundreds of parameters are tracked throughout the build. They include information about the build chamber conditions, temperatures, electron gun, and raking mechanism. These machines also include the LayerQam system, which captures multiple near-infrared images of the powder bed for each layer. These images can be analyzed to detect certain types of surface-connected porosities.

Layer Metrics

Layer Metrics, a startup, uses a unique amalgam of spectral, interferometric, and imaging techniques to simultaneously monitor melt pool, laser, powder bed, and layer surface characteristics in real time. An optical fiber probe array mounted on the printer captures multi-featured build information, which is transmitted to a remote interrogator instrument with single-camera detection. The system supports closed-loop control based on live data in a compressed format.

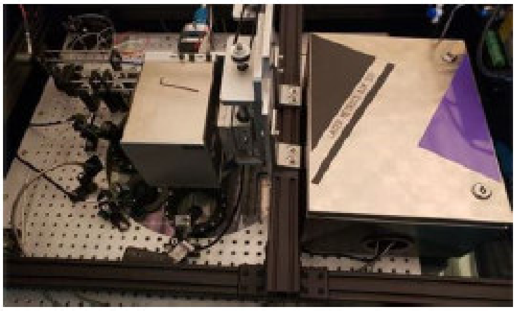


Fig. 193. Process monitoring system, courtesy of Layer Metrics

Manufacturing Demonstration Facility

The U.S. Department of Energy's Manufacturing Demonstration Facility at Oak Ridge National Laboratory (ORNL) is licensing Peregrine, a printer and sensor-agnostic data analysis tool for PBF systems. Multi-modal layer-wise image data can be co-registered, fused, and analyzed for anomalies using deep learning pixel-wise segmentation algorithms. Anomaly detection occurs in real time throughout the printing process. Temporal data, part features, scan path information, and metadata are combined with the segmentation results in a common interface and suite of visualizations.

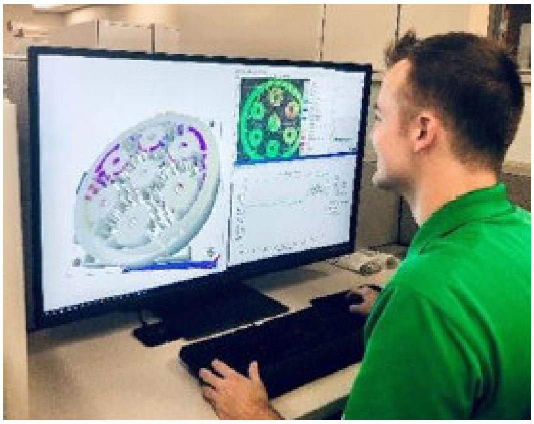


Fig. 194. Peregrine's visualization interface, courtesy of the Manufacturing Demonstration Facility at ORNL

Open Additive

The company is dedicated to developing systems with open architectures. Its laser-based PANDA printers include the AMSENSE module, which collects visible-light images of the powder bed immediately after layer fusion and after powder spreading. The company also includes an application programming interface. It allows users to integrate their own data analytics code and multiple user-accessible viewports on the top of the machine.

The optional TOMOTHERM module images the build area using an off-axis near-infrared camera during layer fusion. By capturing data at a moderately high frame rate, a single composite image can be constructed for each layer. The SPAT-TRAK module uses a medium-speed thermal imaging system to capture spatter events and spatially map them.

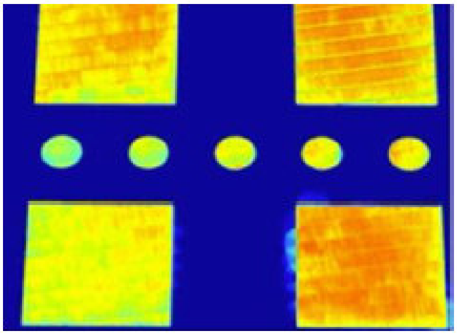


Fig. 195. Thermal tomography from a single layer, courtesy of Open Additive

Phase3D

Phase3D (formerly Additive Monitoring Systems) is a startup company developing a new, low-cost sensor capable of performing high-resolution topological measurements of the powder bed. These measurements can then be analyzed to detect flaws or other process anomalies. Their sensor and software solutions are intended as third-party installations on existing PBF and BJT printers.

Renishaw

Renishaw's latest laser PBF systems are equipped with InfiniAM Central, which logs information on machine health, machine productivity, and build chamber conditions. This data can be streamed in real time and compared across multiple print jobs and printers. Renishaw machines are also equipped with LaserVIEW and MeltVIEW modules. They use multiple photodiodes, sensitive to different wavelengths, to measure laser output and melt pool thermal emissions, respectively. This data can be analyzed using the InfiniAM Spectral software, which can give insight into off-nominal conditions and processing defects.

Sigma Additive Solutions

Sigma Additive Solutions (formerly Sigma Labs) is a third-party provider of laser PBF hardware and software process monitoring solutions. The company's PrintRite3D system is based around multiple complementary on-axis and off-axis photodiodes, which are sensitive to specific wavelength ranges. By combining thermal emissions data from multiple sensors, local temperatures around the melt pool can be estimated.

Sigma Additive Solutions has developed several complementary quality metrics, which can be used to detect off-nominal printing conditions and flaws. The system relies heavily on edge computing for real-time data analysis and visualization. Efforts are underway to train machine learning algorithms to improve the system's defect detection capabilities. The company has also recently begun directing efforts toward off-axis sensor development and new machine learning-based anomaly detection algorithms.

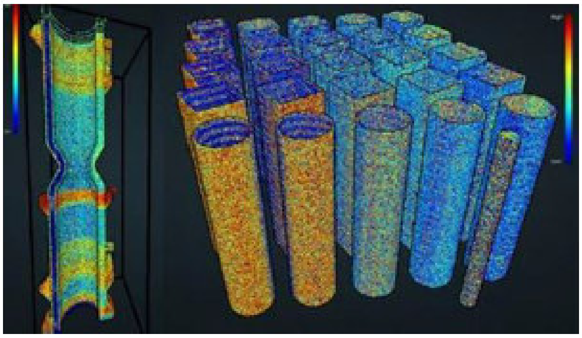


Fig. 196. Thermal emission density mapping, courtesy of Sigma Additive Solutions

SLM Solutions

The process monitoring system from SLM Solutions includes the Layer Control System (LCS), Laser Power Monitoring (LPM), and Melt Pool Monitoring (MPM). LCS logs machine health information as well as conditions inside the build chamber. The system also captures visible-light images of the powder bed.

LPM uses an on-axis photodiode to continuously monitor laser power throughout the build and compare it to the commanded laser power. MPM uses a second on-axis photodiode to capture thermal emissions from the melt pool, vapor plume, and surrounding region.

Velo3D

Velo3D's Assure software monitors the health of the machine, confirms the parts are of good quality, and documents this information for the end-user. The company's Sapphire printers perform automatic laser calibrations for each build. To reduce the need for support material, the system monitors powder bed topology, detecting variations and issues.

Zeiss

Zeiss recently partnered with EOS to provide additional process monitoring capabilities. The system from Zeiss consists of a high-resolution visible-light camera, which replaces the EOS POWDERBED camera. It includes additional, multi-directional lighting within the build chamber. Zeiss has also developed a deep learning segmentation algorithm that can detect anomalies using this imaging system.

Outlook

Industry deployment of on-axis sensors is rapidly becoming standard for laser PBF machines. The industry's focus for many years was geared toward the development of on-axis sensors. In 2022, however, the most significant commercial announcements were related to off-axis sensors and new software tools. Printer manufacturers and third-party entities are increasingly recognizing that users require software assistance to translate the complex in-situ sensor data into actionable information.

The detection of millimeter-scale powder bed anomalies is close to maturation. However, the detection of anomalies smaller than 100 µm (0.004 in) and effective measurement of thin-walled structures require higher-resolution imagers than those typically installed by the machine manufacturers. Perhaps the greatest sensing challenge remains robust detection of relatively small, subsurface porosity in laser PBF processes. For electron beam systems, near-infrared imaging can be effective. Fortunately, industry and research institutions are investing a large amount of effort in this specific area.

The PBF community will need to develop procedures for qualified data collection and storage of extremely large datasets as part of a digital twin approach. Creation of the born-qualified paradigm will also require identifying the correlations between observed in-situ process signatures and ex-situ measurements and part performance. Developing this capability will require additional research into rapid characterization of AM parts and integration with physics-informed modeling.

As with all QA programs, monitoring techniques require validation. Due to recent reliance on machine and deep learning techniques for flaw and defect detection and correlation, additional scrutiny from regulatory bodies can be anticipated. Currently, both industry and funding agencies are offering strong support for research aimed at solving the most pressing PBF process monitoring challenges.

Post-processing

Post-processing encompasses manufacturing and finishing steps that occur after building parts on a system. Post-processing is a significant part of 3D printing. Those less familiar with AM will often discount the time, cost, and importance of post-processing. 3D printing is not a "pushbutton" technology. It is a collection of processes, techniques, and specialized skills necessary to produce quality parts.

The three basic steps in the AM process are pre-processing, part building, and post-processing. The first and third are detailed in the following tables. Use of specific pre- and post-processing steps depends on the application and specific part requirements.

Pre-processing

Metal powder bed fusion	**Polymer powder bed fusion**	**Material extrusion**	**Vat photo-polymerization**	**Directed energy deposition**	**Material jetting**	**Binder jetting**
Check quality of files and repair if necessary	Check quality of files and repair if necessary	Check quality of files and repair if necessary	Check quality of files and repair if necessary	Check quality of files and repair if necessary	Check quality of files and repair if necessary	Check quality of files and repair if necessary
Prepare job in software by arranging parts on build platform and generating support structures	Prepare job in software by arranging parts on build platform	Prepare job in software by arranging parts on build platform and generating support structures	Prepare job in software by arranging parts on build platform and generating support structures	Prepare job in software by arranging parts on build platform and generating support structures	Prepare job in software by arranging parts on build platform and generating support structures	Prepare job in software by arranging parts on build platform
Clean AM system	Clean AM system	Clean AM system	Clean AM system	Clean AM system	Clean AM system	Clean AM system
Purge and preheat build chamber	Purge and preheat build chamber	Preheat build chamber	–	Purge and preheat build chamber if inert atmosphere system	–	Preheat build chamber if necessary

Post-processing

Metal powder bed fusion	**Polymer powder bed fusion**	**Material extrusion**	**Vat photo-polymerization**	**Directed energy deposition**	**Material jetting**	**Binder jetting**
Remove build plate from build chamber	Find and remove parts from powder bed	Remove parts from build chamber	Drain and recycle unused material as applicable	Remove build plate from build chamber	Remove parts from build chamber	Find and remove parts from powder bed
Remove loose powder and recycle as applicable	Recycle remaining powder as applicable	Remove parts from build plate	Remove parts from build chamber	Thermal stress relief, if required	Remove support material mechanically through waterjet or dissolution	Recycle remaining powder as applicable
Thermal stress relief	Media-blast parts to remove surface powder	Remove support material	Wash off excess uncured resin in chemical bath	Remove parts from build plate	Finish surface: sand, paint, etc.	Air-blast parts to remove surface powder
Remove parts from build plate	Finish surface: tumble, sand, dye, paint, etc.	Surface finish: sand, vapor smooth, paint, etc.	Remove support material	Hot isostatic pressing	Inspect	Chemically debind metal parts (process dependent)
Hot isostatic pressing	Inspect	Inspect	Post-cure in ultraviolet light chamber	Remove support structures	–	Bake or sinter metal parts as necessary
Remove support structures	–	–	Finish surface: sand, paint, etc.	Heat treat as necessary	–	Strengthen by infiltration for gypsum parts
Heat treat as necessary	–	–	Inspect	Surface machine, shot peen, abrasive flow machine, etc.	–	Finish surface: sand, paint, etc.
Surface machine, shot peen, abrasive flow machine, etc.	–	–	–	Inspect	–	Inspect
Inspect	–	–	–	–	–	–

Source: Wohlers Associates

Polymer post-processing steps

Depending on the AM system and the intended application, some or all of the following post-processing steps are necessary:

Support Removal: Most polymer AM systems, except for PBF and some BJT processes, require sacrificial support structures during the build process. They are then removed after the build is complete. This is typically done using a variety of hand tools and mechanical force. With some systems, remove supports by dissolving them in a liquid bath or using a waterjet.

Surface treatment: Most parts require some form of surface treatment to achieve an acceptable surface. This can include sanding, machining, dyeing, painting, and several other surface treatment techniques.

Metal post-processing steps

Depending on the intended application, some or all of the following post-processing steps are necessary:

Support removal: Most metal AM systems, except for some BJT systems, require sacrificial support structures during the build process. With PBF systems, they act as a heatsink to dissipate heat and resist the mechanical force of the powder spreading mechanism. They also anchor the part to the build platform to prevent upward distortion into the path of the powder spreading mechanism. Support structures are removed after the build process is complete. This is typically done using a range of hand tools and mechanical force or the use of a bandsaw or wire EDM.

Heat treatment: Most metal AM processes are based on thermal processing, so a high level of residual stress can be induced in the parts during the build process. To avoid distortion, the parts go through a stress-relieving process before they are removed from the build platform. This process typically involves a slow warming phase, a soaking period, and a slow cooling stage. The soaking period usually lasts between one and several hours, depending on the thickness of the part. Thick and thin sections of a part should cool at the same slow rate to prevent the formation of residual stresses.

Surface treatment: Most parts require some form of surface treatment to achieve acceptable surface quality and the required engineering tolerances. This includes CNC machining, filing and grinding, and several other surface treatment techniques. Further heat treatment may be necessary to achieve the required mechanical properties.

See the following page for more detailed information on post-processing:
https://wohlersassociates.com/product/postprocessing2023

AM part inspection

by Alex Doukas

Part inspection is an important step in the AM value chain. Two primary approaches are non-destructive testing (NDT) and destructive testing. NDT is often a more appealing option so that parts are not destroyed. Frequently used methods for data acquisition include coordinate measuring machines (CMMs), CT scanning, structured light scanning, and laser scanning. Each method has its benefits and limitations. Depending on the part's geometric complexity, more than one method may be needed for complete inspection.

CMMs offer high accuracy and repeatable data acquisition to assess exterior features. The technique uses either a manual or automated contact probe. This technology requires surface contact and fixturing, which can damage fragile parts. Some versions of CMMs include a non-contact optical scanning head in place of a contact probe.

Non-contact methods to inspect exterior features include structured light and laser scanning. Of the two, laser scanning is more popular. Both techniques employ triangulation methods using a light source and a camera or sensor. With structured light, a line or pattern of light is projected onto the surface. The line remains straight from the viewpoint of the light source. However, from the vantage point of the camera, the line is distorted, detecting the topography of the part. Laser scanning uses a laser to project a spot or line onto the surface of a part. Using triangulation, a sensor infers the distance to a projected line or spot.

Fig. 197. Example of a laser scanning system actively collecting data, courtesy of Carolina Metrology

Structured light and laser scanning systems capture millions of data points accurately and quickly. The data can be analyzed to obtain critical dimensions, which can be compared to a part's designed dimensions. These scanning processes use line-of-sight data acquisition, which makes them impractical to inspect some geometric features, such as undercuts, deep pockets, and holes. Both non-contact scanning techniques may require processing of a part's surfaces to reduce the effects of reflections. Polymer and metal parts with a matte finish are most suitable for these inspection techniques.

Fluorescent penetrant inspection is another method used to inspect metal AM parts. A dye is applied to the exterior of a part, which highlights surface anomalies and/or layer separation. This method cannot inspect interior features.

Some methods, including radiography and CT scanning, are useful to inspect both exterior and interior structures. Radiographic X-ray inspection can be used for quick qualification of interior structures. It is also used for verification of internal features. Radiography is a quick and efficient way to capture geometric features and typically requires only a few seconds to gather data.

CT scanning is a method of NDT in which a 3D dataset is created by combining a series of 2D X-rays. CT is used to inspect the entire part. High-power CT systems are used for dense metal parts. The following shows renderings of a 3D-printed test coupon. The part has been inspected using industrial CT to probe internal feature accuracy.

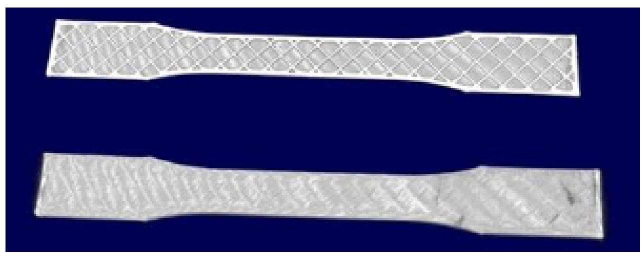


Fig. 198. 3D rendering of CT data of a tensile bar (bottom) with a cross section through the volume (top), courtesy of Kinetic Vision

A benefit of CT inspection is capturing internal volumetric features. Results can be used for evaluating dimensional accuracy, porosity, microcracking, layer structure, delamination, and material distribution. CT is an excellent method for R&D and limited production part inspection. Constraints, such as cost, time, and accessibility, result in less frequent use of CT for high-volume production environments.

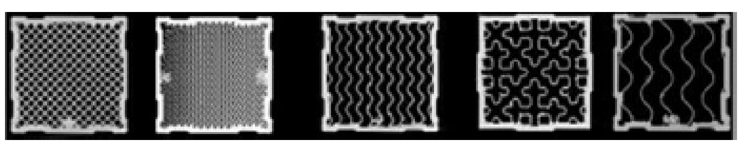


Fig. 199. Internal structures of AM parts validated using industrial CT scanning, courtesy of Kinetic Vision

Each inspection method has specific benefits and tradeoffs. The method should be chosen on a case-by-case basis depending on several factors. They include the required accuracy, the need to inspect internal volumes and/or features, material properties, time, and cost. Inspection methods and techniques are constantly improving to meet the needs of the AM market.

Costs and challenges

The benefits described near the beginning of this part justify the use of AM for series production by increasing product value. However, challenges associated with AM can often nullify these benefits if not managed properly.

Operating costs

Two primary expenses are machine time and materials. Most AM machines suitable for final part production are expensive to purchase, operate, and maintain. Machine depreciation usually spans several years and is divided among all parts built in that time interval.

The high cost of AM machines is attributed partly to the relatively small number being sold. The vendors need to recuperate development costs. If machines were produced and sold in much larger volumes, the unit price would surely decline. This has been the case with desktop 3D printers from China. The AM industry is experiencing increased competition, which favorably impacts product pricing for customers.

Some AM materials are expensive because they are costly to produce. Production volumes are also relatively low compared to materials for conventional manufacturing. However, thermoplastics used in material extrusion (MEX) are commonly used for injection molding and should be relatively inexpensive. Even so, AM suppliers price MEX filaments many times higher than injection molding pellets. In this case, the cost to the customer is believed to be artificially inflated.

AM system manufacturers often incentivize customers to use their materials exclusively. They may use warranties and software lockouts to discourage the use of competing materials. Material costs will decline when true competitive market conditions and economies of scale are realized.

Cost justification

A key to success with AM is comprehensive and realistic cost justification. When making a simple one-to-one cost comparison between AM and conventional processes, the range of parts for which AM is suited is small. A business case for AM usually fails when relying solely on this approach. Instead, consider the broader product life cycle and total manufacturing cost.

Cost is often justified when a part must be put into service quickly. Out-of-service commercial aircraft, trains, and drilling rigs can incur substantial costs in lost revenue. In some instances, a $10,000 AM part can be justified if equipment returns to full service quickly. For this reason, some companies are developing part databases and production workflows to support on-demand spare part production. These databases are not easy to create and require significant upfront cost and time. Parts in a database must be thoroughly vetted to ensure quality and safety.

It may be difficult to initially justify the deployment of an airplane part that costs $1,000 when made using AM compared to a $500 casting. However, if weight is reduced by 25%, resulting in savings of $2,000 over 10 years of operation, a business case becomes more likely. Similar arguments are possible for improvements in product performance, greater customer satisfaction, reduced product maintenance, and a reduction in total manufacturing costs.

Machine throughput

Another way to reduce the cost of AM parts is to increase machine throughput. This can be increased with faster operating speeds, larger build volumes, optimizing part packing in build chambers, and automating the removal of parts from the machine. Many metal PBF system manufacturers provide machines with multiple lasers to speed the build process. Among them are Additive Industries, EOS, GE Additive, SLM Solutions, and Trumpf.

Another approach to improving throughput is to use continuous production techniques. Creality's 3DPrintMill and the 3D printer from Blackbelt demonstrate the continuous building of parts using a conveyor belt. These machines can run nearly non-stop and can build extremely long parts.

Metal part production cost considerations

Metal part production using AM presents challenges and is typically costly. The build is one of typically 10 or more steps that require both proper equipment and experience.

Metal AM machines range from about $65,000 for a small, basic configuration to more than $2 million for one that produces large parts. Ancillary equipment and experienced personnel are expensive. Increased competition in metal AM products and services is beginning to force prices downward some, but not a lot.

Metal AM workflow can include heat treatment, CNC machining, and other equipment and processes. The following table provides a list of processing equipment and estimated price ranges.

Equipment	Estimated price
Metal and polymer PBF	
Explosion-proof vacuum cleaner	$2,000–30,000
Powder sieving system	$5,000–30,000
Shot peening and/or sand blasting (manual or automated)	$5,000–100,000
Polymer PBF	
Powder mixing system	$5,000–30,000
Metal PBF	
Inert gas (typically argon or nitrogen)	$12,000 per year
Furnace for heat treatment	$5,000–100,000
Polishing systems	$1,000–60,000
Bandsaw, wire EDM, hand tools	$500–200,000
CNC machining center	$20,000–100,000
Class D fire extinguisher	$1,000
Metal BJT and MEX	
Chemical or thermal debinding system	$50,000–150,000
Furnace for sintering	$50,000–150,000
Furnace for heat treatment	$5,000–100,000

Equipment	Estimated price
Polishing systems	$1,000–60,000
CNC machining center	$20,000–100,000
Powder sieving system	$5,000–30,000
Material jetting (MJT), MEX, and VPP	
Isopropyl alcohol cleaning system	$50–50,000
Ultrasonic cleaner for wax support removal	$500–20,000
UV curing chamber	$3,000–30,000
Vapor smoothing	$5,000–300,000

Source: Wohlers Associates

Other equipment and supplies include:

– Air compressor required for majority of systems
– Climate control (both temperature and humidity)
– Hand tools
– Part quality analysis systems (e.g., testing of hardness, tension, surface roughness, and dimensional accuracy)
– Power infrastructure and metering
– Personal protective equipment (PPE) and supplies
– Safety control, gas sensors, and disabling sprinkler systems
– Special powder storage, particularly for reactive powders
– Three-phase and single-phase electricity

Sieving equipment for powder recycling is an important part of a metal AM system. Some machine manufacturers bundle it with the price of the machine, while others do not. It is important to understand what is included with the machine. Knowledge of the AM process steps and "hidden" costs helps ensure a system transaction takes place smoothly for both the buyer and seller.

Fig. 200. AMPro sieve station, courtesy of Russell Finex

Most metal PBF systems operate in an inert atmosphere to reduce the possibility of contamination from oxygen and carbon dioxide in the air. Argon gas, nitrogen gas, a vacuum, or a combination is used to eliminate unwanted gases. The cost of argon gas can exceed $12,000 per year to support one metal AM machine. The actual cost depends on local gas prices, the way in which the AM machine is used, and the size and throughput of the machine. If nitrogen is used, the gas can be obtained either from gas bottles or from a nitrogen generator.

Fig. 201. Inert gas containment enclosure at the University of Auckland

Safety considerations

Metal PBF systems require several safety considerations. One concern is the safe use of reactive powders, such as titanium and aluminum. Both can ignite, burn, and even explode under certain conditions. It is important to take special safety precautions when using these types of powders. A class D fire extinguisher is required, at minimum. Storage of powders, especially in large quantities, comes with special requirements that can be expensive.

PPE is required to protect machine operators and technicians from exposure to metal powders. It can range from a few hundred dollars for gloves and face masks to thousands for full-body suits with built-in air filtration. Some metal PBF systems come with built-in powder management systems to reduce contact with powder. Aftermarket powder management systems are also available from several suppliers.

Fig. 202. PPE for metal PBF, courtesy of Materialise

Facility considerations

Metal PBF systems operate optimally when the ambient temperature and humidity are maintained at levels recommended by the machine manufacturer. Air conditioners, humidifiers, and dehumidifiers are usually necessary. Initial costs can be in the range of $10,000, but this can vary greatly depending on the size of the room where the machines are installed.

A building may require alterations to accommodate metal AM systems. In some cases, it may be necessary to widen doorways, strengthen floors, and remove walls so the machines can be moved into place. Proper ventilation is necessary to reduce hazards associated with fine powders becoming airborne. Machine weight is a consideration because it impacts its location and access for maintenance.

New gas lines and electrical capacity are often required when installing metal PBF systems. For reactive metal powder, consider disabling a sprinkler-based fire extinguishing system because metal powder can react dangerously to water. It may be advisable to install sensors to detect the level of gases, such as oxygen, in the air. If an argon gas leak occurs, it could quickly cause asphyxiation, particularly in a small room.

Additional equipment

An industrial air compressor is often required and can cost $30,000. A sandblaster is needed to remove powder attached to parts and can cost $12,000. A shot-peening cabinet, which can cost $15,000, is useful for improving the surface finish of parts. Industrial vacuum cleaners are also required and can cost $19,000. It is important they are intrinsically safe and can be used with reactive powders.

A heat treatment furnace will cost $15,000–30,000, and one used for titanium can cost $100,000. Equipment is needed for removing parts from the build plate, such as a bandsaw

($10,000–25,000) or a wire EDM system ($50,000–200,000). Electricity can cost $3,000 or more annually, depending on local pricing and the amount used.

When hot isostatic pressing (HIP) is necessary for metal parts, it is usually outsourced. However, be sure to budget this expense for aerospace and certain other types of structural parts. HIP systems can cost $1.5–3 million. Software licensing fees can be $3,000 annually, but they too can vary widely, depending on the software purchased.

Annual maintenance contracts for an AM machine can range from $10,000 to more than $30,000, depending on the level of service. Maintenance contracts extend the warranty beyond the first year of ownership. The cost of filters for a metal PBF machine can be $30 each, but some can cost as much as $7,000. Other consumables include build plates, recoater blade wipers, and lasers.

Carefully consider all costs associated with metal AM part production. It is critical to successful implementation in a profitable business. When considering the purchase of AM machines, speak with experienced customers to better understand the real costs involved.

Qualification and quality

Rigorous and consistent production quality control is always critical, especially in highly regulated industries such as aerospace and healthcare. The qualification of new processes and materials can be time consuming, complex, and expensive. AM parts must satisfy the same regulatory standards of acceptance as conventionally manufactured parts. Regulations and standards often dictate the level of defects, material properties, traceability, and process certification that new solutions must meet. AM technologies do not necessarily suffer from an absence of capability, but from a lack of consistency and an insufficient body of supporting data.

AM can create high-quality parts, but repeatability and reliability issues remain. A lack of process monitoring and control is partly the cause. To address these and other issues, the international effort to develop standards for AM continues. ASTM International started working on AM standards in 2009, while ISO began in 2011. The primary standards development committees are ASTM Committee F42 on Additive Manufacturing Technologies and ISO/TC 261 on Additive Manufacturing. For details on how to inspect parts, see the section titled "AM part inspection" within this part of the report. For details on industry standards, see the section titled "AM standards" in Part 6.

Educating designers

How one thinks about design changes when working with AM. Designers can concentrate more on functionality and less on manufacturability. Address education and training through published guidelines, industry standards, courses, and hands-on learning.

Individuals and organizations have tried to create comprehensive AM design guidelines, but it is difficult to cover all available AM materials and processes. System manufacturers and service providers have created guidelines for specific processes. Olaf Diegel has documented many guidelines in his book titled *A Practical Guide to Design for Additive Manufacturing*. An ASTM/ISO working group is producing a standard guide on designing for AM.

Wohlers Associates has produced its own version of DfAM guidelines for its training and hands-on learning. Olaf Diegel, lead instructor of the courses, stresses repeatedly that guidelines can only help form an intuition for design and will never replace hands-on practice.

Fig. 203. Instructor Olaf Diegel presenting at a Wohlers Associates DfAM course in Frisco, Colorado

DfAM education can occur at many levels, starting at ages 12–15, through to colleges and universities and on-the-job training. The sooner DfAM is introduced to a designer, the better. Experienced designers know how to make products look and work, and most will understand the benefits of AM.

A shortage of DfAM educational and training resources worldwide is apparent. In response to this, Wohlers Associates began to conduct DfAM courses for NASA and other organizations in 2015. The two- and three-day courses are tailored to the specific needs of the group. As of February 2023, the company has conducted multi-day DfAM courses in Australia, Belgium, Canada, Germany, South Africa, South Korea, and the U.S.

Scaling AM into production

by Doug Collins and Greg Morris

Many companies are moving toward AM for final part production. Scaling from prototyping to series production typically requires changes and upgrades to methods and tools. Among them are software, post-processing, maintenance, quality control, finishing capabilities, and staff training.

Production systems

Scaling AM to production volumes can be difficult, although it does not inherently require purchasing more machines. Using existing systems more efficiently can increase throughput. Some AM processes are better suited to series production than others.

For polymers, PBF systems support the nesting of parts in 3D space because the surrounding loose powder serves as support material. Many parts can be printed in a single build, which can result in increased productivity. Care must be taken when considering full-chamber builds to avoid running out of powder near the end of the build. This occurs when insufficient powder is transferred to the powder bed as layers are spread. Some PBF systems increase output by printing a full-width layer in a single pass. For laser PBF systems, multiple lasers result in faster build times.

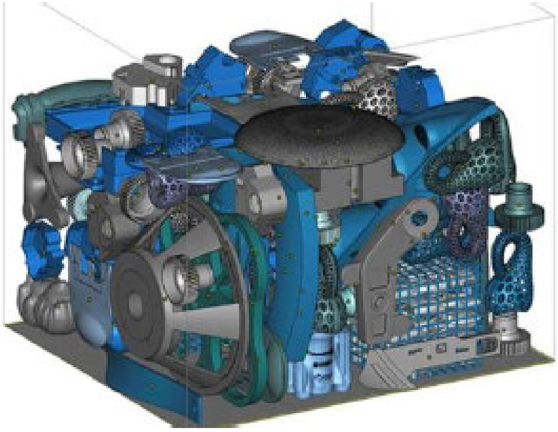


Fig. 204. Part nesting using Nester module, courtesy of Materialise

AM processes use different methods to increase production rate. Digital light processing (DLP)-based systems arrange the most parts possible on a build platform. Unlike PBF, they typically do not nest parts vertically, as shown in the previous image. This is because the additional support material can become nearly impossible to remove after the build is complete. DLP system manufacturers are introducing products with larger build volumes to accommodate more parts per build. Multiple lasers are used with large VPP systems to increase speed and throughput.

For MEX, multiple units running in tandem as a print farm can reach series production rates. This approach is also used with VPP and PBF systems. MEX printers have been developed with large build chambers and multiple print heads to increase throughput.

Metal AM system makers are focusing on increased build platform size coupled with high-energy deposition. This has been achieved through high power and/or multiple energy sources. For example, instead of having one or two lasers, PBF systems support four or more lasers. The result is faster scan times for each layer and faster throughput.

Some AM system manufacturers have integrated automation into their equipment to maximize build times. For example, a modular build platform may be removed automatically from the machine and quickly replaced with another. Some systems include central powder handling and automated sieving and mixing of new and used material. This streamlines labor-intensive effort and improves operator safety.

Fig. 205. Automated build platform changing, courtesy of 3D Systems

Software

Nesting algorithms and MES software are critical for scaling AM into production. Nesting algorithms help arrange parts digitally in 3D space before printing. Part orientation is determined based on surface finish, tolerance, and material properties.

MES software tracks parts from an initial quote to the delivery of parts. This includes build planning and control, machine monitoring, error tracking, post-processing, and quality control. These software tools become essential for tracking materials, parts, and capacity, especially as production quantities increase. This improves quality and fosters better communication with customers.

Staff and maintenance

Experienced staff can make a difference in part quality, customer service, and support. Labor-intensive aspects of the AM process include pre-production (e.g., nesting parts and production scheduling), printer operations, post-processing, and quality control. Equipment is typically operated at the highest capacity possible for series production. Both preventative maintenance and rapid equipment repair require skilled staff to prevent significant downtime.

Companies are advised to invest in quality training to ensure equipment operators and technicians have a high level of knowledge and skill. This includes in-depth training on determining the best location and orientation of parts to optimize mechanical properties and surface finish. Minimizing the need for support material is another important factor. These skills take time to master and are critical for a smooth and profitable operation.

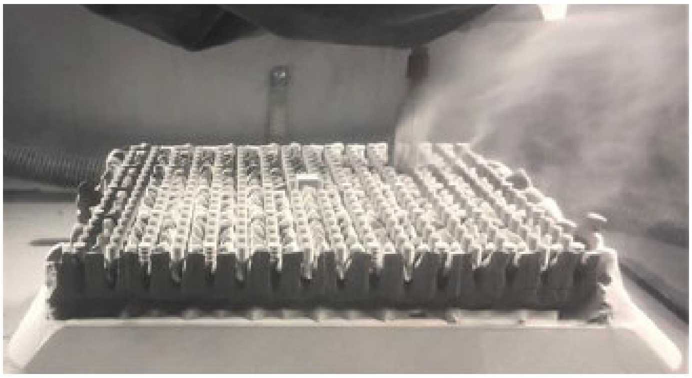
Engineers and technicians can receive machine maintenance and repair training from most equipment manufacturers. It is important for production teams to maintain a close working relationship with the equipment manufacturer's service department. Rapid access to spare parts is essential to scale AM to minimize machine downtime.

Post-processing

Post-processing typically requires more manual labor than any other part of the AM process chain. Companies offer automated equipment to reduce the time and labor needed for post-processing.

Depending on the final application, each AM process requires one or more post-processing steps. Support material is removed, and parts are typically cleaned, cured, and/or depowdered. For parts made by MEX, automated systems help with soluble support structure removal. Parts made by PBF benefit from automated bead blasting systems and tumblers to remove unfused powder and improve the surface finish.

Fig. 206. DPS 1000 depowdering station, courtesy of Digital Metal



Metal AM part post-processing typically requires machining to achieve specific tolerances and surface finishes. Currently, the vast majority of metal AM parts are created using laser or electron-beam PBF processes, although BJT is gaining traction. With PBF, support structures are made from the same material as the parts being built. In a production environment, support removal will likely require machining.

Another factor to consider when working with metals is thermal post-processing. Stress relieving while parts are still attached to the build platform is necessary for PBF builds, while BJT parts require a post-process sintering operation. After thermal post-processing, PBF parts are removed from the platform using wire EDM, a bandsaw, or another cutting method. Options are often available to automate these activities. Some metal parts require heat treatment to produce acceptable microstructure and service properties.

Finishing

Production parts may require extensive finishing, which adds significant value. However, finishing can be labor intensive and expensive.

Some parts require threaded inserts or assembly with other parts to create subassemblies or finished products. Dyeing can be used to add color to polymer PBF parts and can be partially automated to reduce labor. Coating is a finishing technique in which parts are sprayed in a paint booth by skilled staff. Coatings add color, scratch resistance, UV protection, electrostatic discharge protection, and a desired sheen.

Any AM part surface not machined or otherwise post-processed will likely have some degree of stair-stepping on the surface. Finishing these surfaces is often required either to improve part aesthetics or, in some instances, mechanical properties. Reducing surface roughness can improve fatigue properties and eliminate potential flow obstructions.

Fig. 207. Metal AM part before surface finishing (left) and after (right), courtesy of Comco

Quality control

Quality control (QC) becomes a much larger and more involved task when scaling to manufacturing quantities. It is important to control dimensional accuracy, printing defects, support and powder removal, part cleaning, and mechanical properties. Special tools are often required for QC. They include metrology equipment, 3D scanners, mechanical testers, and various measurement tools to check dimensions and tolerances.

Specialized equipment is needed to monitor feedstock quality. For example, a metal powder particle size analyzer will confirm the size, shape, and powder particle distribution. Measuring these parameters is critical to consistently producing quality AM parts. Tracking possible differences from one batch of feedstock to another, using software and control procedures, is important for proper handling and QC.

Some AM production systems integrate QC checks into the printing process. Examples are in-process thermal imaging, parameter checking, and adjustments during the build.

Fig. 208. InfiniAM Spectral process monitoring software, courtesy of Renishaw

Industry certifications play an important role when scaling AM to production levels. Many industries and customers require ISO 9001 certification, which ensures a quality management system. It enhances business processes and provides a framework for ongoing process improvement.

Some industries require specific certifications. For example, ISO 13485 applies to medical device manufacturing and AS 9001 to aerospace part production. Implementing these certifications requires significant time, training, and investment. Maintaining certifications requires a commitment from the entire organization.

It is sometimes necessary to qualify each machine prior to producing parts for highly regulated industrial applications. Typically, qualifications are performed for installation, operation, and system performance. Four months of effort may be required to qualify a machine for production, depending on the extent of the qualification tests. Once qualified, a standardized plan is used to maintain consistent performance. The plan typically includes regular quality checks and machine monitoring.

ASTM International and ISO have partnered to create standards specifically for AM. The ASTM F42 and ISO/TC 261 committees on AM have collaborated for years to develop and support standards to promote AM adoption. As end-use part production increases, standards will drive market acceptance by providing guidance, consistency, reliability, and safety.

PART 5: GLOBAL REPORTS

An estimated 34.9% of all industrial additive manufacturing (AM) systems installed worldwide are in North America. Research by Wohlers Associates shows that 28.4% of all industrial systems are installed in the Asia/Pacific region. Meanwhile, 30.7% are in Europe, with the remaining 6.0% installed in Central America, South America, the Middle East, and Africa.

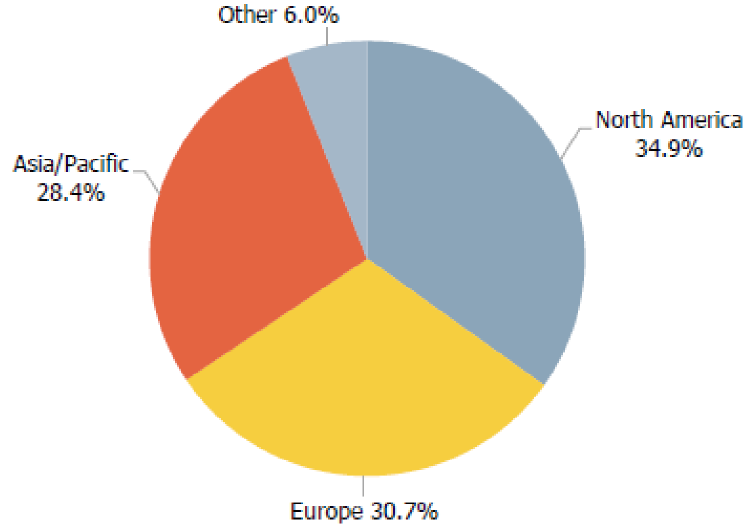


Fig. 209. AM system installation base by region; source: Wohlers Associates

Installations by country

The following graph estimates, by percentage, the number of industrial AM systems installed by country. The estimates are cumulative totals from the technology's inception through 2022. Used system sales have been excluded from the estimates so machines are not counted more than once.

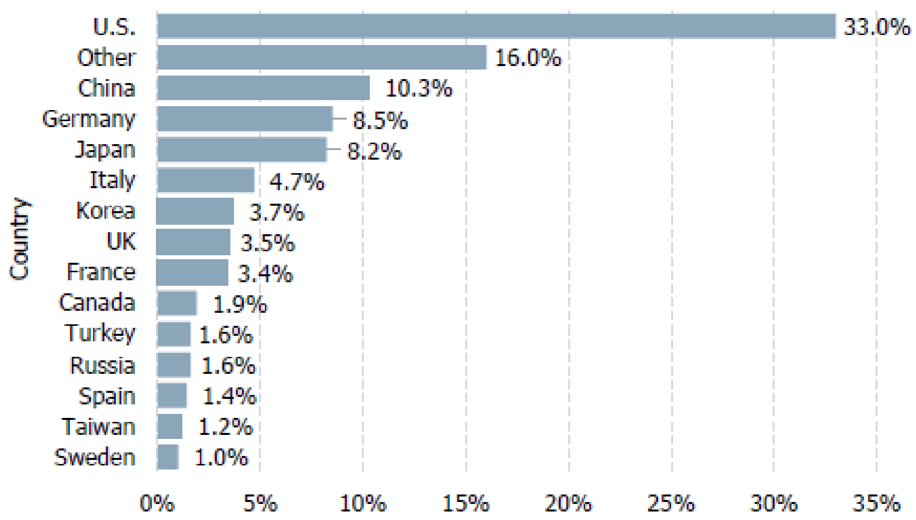


Fig. 210. AM system installation base by country; source: Wohlers Associates

The U.S. continues to serve as home to more than three times the number of industrial AM systems than any other country. China, Germany, and Japan have the next largest installation base of machines.

Many AM system manufacturers and service providers worldwide provided the data used to produce the previous charts. This information, coupled with data from third-party material producers, manufacturers of desktop 3D printers, and others, was used to complete other sections of this report. This information represents 28 years of collecting and analyzing data, which is unique to the AM industry. No other organization in the world has access to this breadth and depth of data and market intelligence on AM. It is used to track industry growth, provide historical perspective, uncover trends, and offer insight into the future of this exciting industry.

Africa

by Deon de Beer, Devon Hagedörn Hansen, and David Bullock

Two oil and gas companies are investing in AM capacity in West Africa to combat supply chain issues and promote localization. South African AM companies Rapid 3D and HH Industries are collaborating on a project to increase AM adoption in Nigeria. Two more metal powder bed fusion (PBF) systems are due to start operating in Nigeria in 2023. This will bring the total number of metal AM systems in the country to three. AM investment has also increased in Kenya and Ethiopia through technology hubs, new 3D printer resellers, and the launching of more AM facilities.

HH Industries, Central University of Technology (CUT) in South Africa, and other partners launched an initiative titled 3D Printing in Africa. It aims to track 3D printing activities across the continent and provide access to resources such as training, service providers, and AM facilities. STEM programs in both the region and outside Africa, including the U.S., are taking advantage of the online training content.

The Education for Laser-based Manufacturing project is funded through the Intra-Africa Mobility Scheme run by the European Commission's Education Audio-visual and Culture Executive Agency. The project assists partner institutes with teaching and research programs centered around laser-based manufacturing systems including PBF and directed energy deposition (DED). CUT has an ongoing collaboration with the University of Botswana and the Botswana Institute for Technology Research and Innovation. The collaboration focuses on the development of AM ecosystems in Botswana, with an emphasis on innovative medical products.

South Africa

by Deon de Beer, Devon Hagedörn Hansen, and Gerrie Booysen

Local niche manufacturers continue to increase their adoption of AM. Capital investment funds are limited, especially in the private sector. Interest in 3D scanning technologies has increased. Some startups focusing on developing AM technologies have emerged. Resellers reported growth in sales to a wider industrial base.

AM continues to be adopted by several major companies for short-run production parts. Notable application areas include producing parts for the localization of fast-moving consumer goods. AM is also being used in the mining and general engineering sectors, as well as in certain niche markets. Due to continuing global supply chain issues, some mining companies are investigating AM for local on-demand production of spare parts. South Africa has seen a significant increase in the number of parts created for unmanned aerial drones. Mass customization of medical implants also gained traction, including the production of large-scale implants known as custom megaprostheses.

Fig. 211. Custom megaprosthesis for partial replacement of the pelvis made using metal PBF, courtesy of George Vicatos, Andre Olivier, and the Centre for Rapid Prototyping and Manufacturing

Five companies in South Africa have developed new AM machines, with material extrusion (MEX) being the dominant process. One company, Aditiv Solutions, has developed and commercialized the Hyrax laser PBF system for metal parts. Another company, Mechatech Engineering Solutions, has developed a concrete 3D printer for construction. The company secured incubation money from a government initiative, with a second funding round underway in early 2023. Since the pandemic, local AM material manufacturing has increased, with three companies producing MEX filament and one company investigating local AM powder production.

The Council for Scientific and Industrial Research (CSIR) has secured about R50 million ($2.7 million) in funding for the purchase of a hot isostatic press facility from Quintus. The funding came through the Department of Science and Innovation (DSI) High-End Infrastructure Programme. CSIR also established a Smart Factory facility to support the development of South African manufacturing. Local AM system manufacturer Aditiv Solutions was the successful bidder in the CSIR's tender process for two metal PBF systems.

The national government supports the South Africa AM Strategy through the Collaborative Programme in Additive Manufacturing (CPAM). In 2022, DSI committed an additional R30 million ($1.6 million) to support CPAM activities through March 2024. HH Industries and Multitrade 3D Systems raised about $500,000 in financing for further expansion of the AM industry into greater Africa. It will also be used to create a privately-funded AM facility to focus on industry adoption, R&D, niche applications, and training.

AM events in 2022 included the annual Rapid Product Development Association of South Africa (RAPDASA) conference and exhibition near Cape Town and several product launches and open houses by local AM system resellers. Five companies who exhibited at the RAPDASA event also displayed their products and services at Electra Mining Expo 2022 in Johannesburg, with 30,000+ attendees.

Americas

The U.S. is consistently among the leading countries in the AM industry. Other countries like Argentina, Brazil, and Canada are also active in the space. The following reports serve as a high-level overview of some of the noteworthy activities in each country.

Argentina

by Emiliano Pagani

The AM industry is growing in Argentina but is still relatively small compared to other countries in the region. Most AM systems installed in the country use either MEX or vat photopolymerization (VPP) technologies. The use of laser-based systems is limited due to the typically higher prices for them.

Several Argentinian companies that make 3D printers also act as service providers. They offer parts in a range of polymers including PVA, high-impact polystyrene, and carbon-fiber-reinforced polyamide (PA). Some companies have developed strategic alliances with international brands. Leading AM companies in the country include CH3D, Chimak 3D, Hornero 3DX, and Trideo.

Fig. 212. 3D-printed bust of Diego Maradona (left) made on Trideo's Big T machine (right), courtesy of Trideo

Aluminum smelting company Aluar and airport operating company Aeropuertos Argentina 2000 have used AM for prototyping, spare parts manufacture, and process optimization. Startup company Mirai 3D is producing medical models of complex anatomies for surgical planning. WeSense has used 3D printing extensively in the development of intelligent CO_2 sensors for air quality measurement.

The Argentine Chamber of 3D Printing and Digital Fabrication promotes competitive development of AM. In October 2022, it gathered for the 6th edition of the Argentine 3D Printing Congress. In December 2022, the Ministry of Science, Technology, and Innovation announced the Inter-institutional Program for Additive Manufacturing for the aerospace and aeronautics sector.

Brazil

by Jorge Vicente Lopes da Silva, Neri Volpato, and Fabio Sant´Ana

Polymer AM is being used more commonly in Brazil across many industry sectors to produce prototypes, jigs, fixtures, tools, and spare parts. The production of metal parts, both directly using AM and through secondary processes, is attracting more attention. However, adoption of AM for end-use parts has been slow. The largest user of AM in Brazil continues to be the medical industry. It is used mainly for dental aligner tools, dental and orthopedic implants, surgical guides and tools, and dental prostheses. To give an idea of the scale of production, one company in the sector is consuming 800 liters (211 gallons) of photopolymer per month.

JBS, the largest meat processing company in the world, is establishing a research center for the 3D printing of meat. Bioprinting startups have increased in number and size. National R&D funding agencies and angel investors are supporting these startups in obtaining the equipment, materials, and training needed for future growth. Other startups are using AM and robotics for furniture manufacture and architecture.

Brazilian government agency FINEP is financing initiatives in the automotive sector to form research networks involving universities and companies. FINEP also launched a $9.5 million project call for the creation of 3D printing labs in universities. Many thousands of low-cost 3D printers have been purchased. The São Paulo State agency FAPESP is supporting startups and small companies with projects related to AM.

Universities are involved in many AM-related projects. They include using NiTi alloy for aeronautic applications and producing parts for the oil and gas industry using wire-arc AM. Other projects involve developing strategies for hybrid processes and materials, and the application of bioprinting. The Institute for Advanced Studies (IEAv) has been developing metal AM parts for use in wind tunnel tests. The leading engineering, manufacturing, and materials science conferences in Brazil have included AM as a key topic.

Fig. 213. A supersonic flow blade made from AISI 430 stainless steel for wind tunnel experiments, courtesy of IEAv

Canada

by Steve Kleimaker

Local talent and ingenuity continue to drive AM innovation in Canada. New companies are helping to increase adoption of AM in various sectors, particularly in energy, mining, and healthcare. Governments are also prioritizing investment in AM at academic and research centers at an unprecedented level.

NGen and NRC IRAP partnered to deliver 54 projects through the Additive Manufacturing Demonstration Program. The program primarily focuses on metal AM but also on engineering-grade polymers such as polyether ether ketone (PEEK), (polyethylenimine) PEI, PA, and fiber-reinforced composites. The first two-story, mixed-use building in North America to be 3D printed in concrete was built on Wolfe Island near Kingston, Ontario. It was constructed by nidus3D and has floor space of 214 m^2 (2,300 ft^2).

University of British Columbia researchers have developed a water-based cellulose paste for use in 3D printers. The bio-sourced material has the potential to replace oil-based polymers in certain applications. Target applications include thermal insulation panels for the construction industry. Aon3D, working with the Canadian Space Agency, used an Aon M2+ 3D printer to produce centrifuges for the Space for Medical Research program. The centrifuges are needed for blood sample preparation as part of research on the International Space Station. It will help determine the impact of living in space on the human body.

Toronto startup Xaba is working with the Automotive Parts Manufacturers' Association on Project Arrow. Within the project, an entire 3D-printed chassis was built for an electric vehicle. The project aims to produce the first car to be made using only Canadian intellectual property. Plastonix and Elemental Recycling partnered to develop a new process that uses several proprietary techniques. Using a series of methods, systems, and chemical agents, it is said to reduce any petroleum-derived material into processable chips or powder for 3D printing.

Red Deer Polytechnic's Centre for Innovation in Manufacturing was awarded C$570,000 ($419,000) in federal funding to acquire a digital light processing (DLP)-based 3D printer. Propulsion technology company Reaction Dynamics received C$4.8 million ($3.5 million) in funding from NGen. Some of the money was used to install the first Velo3D metal AM system in Canada. The system is being used to produce metal parts for an innovative hybrid rocket engine.

Fig. 214. 3D-printed hybrid rocket engine part, courtesy of Reaction Dynamics

In June 2022, Montreal hosted the Holistic Innovation in Additive Manufacturing (HI-AM) conference, Canada's most important AM event. The conference included Canada Makes' first Annual General Meeting since it re-formed, with more than 35 member companies in attendance. The next HI-AM conference is planned for June 2023 in Halifax, Nova Scotia.

United States

by Ray Huff

The U.S. continues to shake off the effects of the pandemic. Large companies have adjusted staffing and strategies. Materials and machine developments continued, with new applications being uncovered and perfected. Investments, partnerships, and mergers and acquisitions have continued at a steady pace.

The U.S. military is constantly exploring new applications of AM. In April 2022, the Department of Defense's Defense Innovation Unit partnered with 3D construction company ICON to build three barracks at Fort Bliss, Texas. In September 2022, the Naval Sea Systems Command used AM machines installed in shipping containers to repair a decommissioned destroyer. The exercise took place at Naval Base Ventura County in California.

In May 2022, the White House launched the highly publicized AM Forward program to encourage the use of AM among American manufacturers. Participating companies include Boeing, GE Aviation, Honeywell, Lockheed Martin, Northrop Grumman, Raytheon, and Siemens Energy. The initiative hopes to reinvigorate U.S. manufacturing through AM implementation. Later that month, ASTM International published a new standard for laser PBF part manufacturing, which is supporting AM's growth.

U.S. automakers made use of AM to bolster the country's production in new ways. In June 2022, General Motors printed 60,000 rear spoiler parts to maintain on-time delivery of the 2022 Chevrolet Tahoe. California's Divergent announced in April 2022 that it is working with eight automotive OEMs to integrate AM for series production.

Many companies downsized near the middle of 2022 in response to a changing economic climate. Among them were Carbon, Desktop Metal, Nexa3D, and Xerox. Meanwhile, finding AM talent remains a priority and challenge for many companies across the U.S.

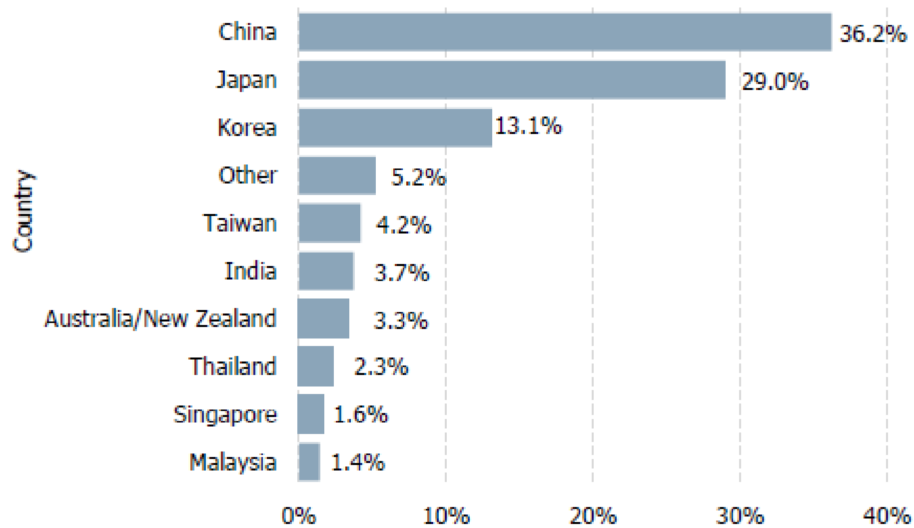
In August 2022, Sakuú announced the opening of a 7,340-m^2 (79,000-ft^2) facility in San Jose, California for producing solid-state batteries using AM. Later that month, the Veterans Administration received FDA clearance to produce 3D-printed models in-house for surgical assistance.

In September 2022, Boeing opened its Center of Additive Manufacturing Excellence in Auburn, Washington to produce aerospace parts. In November 2022, AM service provider Fast Radius filed for reorganization under chapter 11 bankruptcy. The following month, Michigan tooling specialist Sybridge won a bid to acquire certain assets from Fast Radius for just over $17 million, a fraction of the company's former value. Sybridge has operated the company's business since the reorganization.

Asia/Pacific

The following chart shows the cumulative distribution of industrial AM systems in the Asia/Pacific region through the end of 2022. Nearly two-thirds of the systems (65.2%) are in China and Japan. The "Other" segment includes Brunei, Cambodia, Indonesia, Laos, Mongolia, Myanmar (formerly Burma), Nepal, New Caledonia, the Philippines, Sri Lanka, and Vietnam.

Fig. 215. AM installed base of APAC region; source: Wohlers Associates



Except for Japan, the adoption of AM in Asia began much later than in the U.S. and Europe. Companies in Asia were mostly experimenting with the technology in the late 1990s. Most early machine installations in Asia were at technology transfer centers, universities, and training centers. In recent years, the use of AM has progressed rapidly in Asia, especially in China, Japan, Korea, and Singapore.

China

by Feng Lin

The Additive Manufacturing Alliance of China estimates the Chinese AM market grew 24.5% year-over-year in 2022 to reach 33 billion yuan ($4.7 billion). The Ministry of Science and Technology launched the Additive Manufacturing and Laser Manufacturing Program. It is one of several key development programs presented in the national government's 14th five-year plan.

The Ministry of Industry and Information Technology announced 36 target application areas for AM. Twenty are in the industrial sector, 14 in the medical sector, and two in the architectural and cultural sectors. The announcement aimed to guide AM company collaboration, inspire the progress of AM technology and applications, and stimulate new business models.

Investment in the Chinese AM industry continues to grow strongly. According to the Nanjixiong 3D Printing Network, total investment grew 33% year-over-year in 2022 to reach an estimated

6.4 billion yuan ($925 million). In May 2022, the market value of Xi'an Bright Laser Technologies was said to reach $1.86 billion. At the time, this was greater than the market value of 3D Systems or Stratasys.

Exports of AM equipment from China declined in 2022. According to data from China Customs, a total of 1.95 million AM machines were exported from China from January through November 2022. They were valued at a total of around $486 million, which is an 8.05% decrease compared to the same period in 2021.

A research team from Tsinghua University developed a novel 3D printing process to construct a model of the alveolar system. The model was used to mimic the gas/blood interface in the human respiration process, where the COVID-19 virus enters the circulatory system. They developed a new drop-on-demand technique, known as Alternating Viscous and Inertial Force Jetting, to form degradable hydrogel microspheres. With a diameter of about 0.23 mm (0.009 in), the microspheres matched the size of human alveoli.

Huazhong University of Science and Technology has made further progress in developing the 3D Casting, Forging and Milling (3DCFM) hybrid manufacturing system. The latest generation of the 3DCFM machine, the TY4000L, has a build volume of 3.5 x 2.0 x 1.5 m (138 x 79 x 59 in). The system combines a dual-wire-arc metal deposition process with forging and 5-axis milling.

Fig. 216. 3DCFM TY4000L machine (left) and a beam section 3.0 m (118 in) in length in A100 ultra-high-strength steel (right) produced using the machine, courtesy of Huazhong University of Science and Technology

India

by Aditya Chandavarkar

The AM industry in India is maturing slowly. With government support and locally available technology, resources, and expertise, it is expected to grow more quickly over the coming years.

Until recently, most Indian companies using AM were applying it to low-volume production or as a substitution for conventionally manufactured parts. This is changing, with engineering service providers and large OEMs beginning to adopt AM for higher-volume production. This is being driven by the indigenization of defense and local drone manufacturing and wider AM adoption for space applications.

Healthcare and dental applications of AM are expanding. AM is gaining wider acceptance for medical devices and models used for orthodontics, training, and surgical applications. Patient-specific implants are expected to drive further growth. Some startup companies are working in the bioprinting field.

The city of Bengaluru, also referred to as Bangalore, has become established as a leading hub for AM in India. This is due to the early adoption of AM, the presence of large aerospace and engineering organizations, and a thriving startup culture. Other active regions include Delhi NCR region, Hyderabad, Mumbai, and Pune.

The 3D printing startup ecosystem in India is at an early stage. Until recently, most startups were working on polymer MEX technology. However, recent startups are developing hardware, software, and end-use solutions. They include Fabheads, Mira 3D, Mysegmenter, Prayasta, and ThinkMetal. Several startups have received seed funding, but no major acquisitions or investments have occurred.

Indigenization and entrepreneurship technology grants from NITI Aayog, the Ministry of Heavy Industries, and the Ministry of Defense are supporting the adoption of AM. The release of the National Strategy for AM by the Government of India is a major development. The strategy envisages India capturing 5% of the global AM market by 2025, thereby adding nearly $1 billion to the country's GDP. The National Centre of Additive Manufacturing has been launched with support from the Ministry of Electronics and IT and the Telangana State Government.

Intech Additive Solutions and Amace Solutions are engaged in local manufacturing of laser PBF systems. Amace recently announced a hybrid AM system, which combines additive and subtractive processes. Bharat Fritz Werner has launched a range of wire-fed laser DED systems. Fabheads and Deltasys Eforming are manufacturing 3D printers that use polymer composite materials. Deltasys is also producing a concrete 3D printer and a pellet-fed system capable of making large parts. Wipro 3D has launched an industrial MEX system.

Fig. 217. STLR 400 laser PBF system, courtesy of Amace

Indo-MIM produces a range of powders for metal AM. In April 2022, the company received certification for its Inconel 718 metal alloy powder from the Centre for Military Airworthiness and Certification. Saveer Matrix Nano has started producing powders for metal AM. 3DAMSS produces high-performance polymer filaments. Companies manufacturing standard polymer filaments include Augment 3Di, DuchoFilla, and Rever Industries.

AMTech is India's largest AM tradeshow. It was held for the sixth time in December 2022 and attracted over 3,000 visitors. About 70 exhibitors across the AM value chain showcased their technologies and solutions.

Japan

by Hideaki Oba

Despite lingering economic effects from COVID-19, the AM market in Japan continues to grow. Lectures on the use of DED technology were presented by companies in the heavy industry sector. Some automobile manufacturers gave lectures on using a range of AM technologies. The focus of AM activity in Japanese industry is moving from technology investigation to applications. Academic activity covers fundamental research, particularly on AM sustainability, as well as application case studies. Construction companies have started trial AM builds and are investigating the role of regulations.

Two major collaborations were formed in 2022. The Japan Society of Additive Manufacturing was officially established with its membership including 3D printer manufacturers, material suppliers, and user companies. It aims to support further growth of the AM market through the development of technology, quality control, and other crucial production aspects. The Japanese Institute of Additive Manufacturing met for the first time. It is a special interest group within the

Japan Institute of Metals and Materials. Preparations are underway for an official launch in 2026. The group expects to support academic collaborations in general and not only for metal AM.

Nikon Corp. completed its acquisition of SLM Solutions in January 2023. The company has invested in other AM-related companies, including Hybrid Manufacturing Technologies, Morf3D, and Optisys. Sun Metalon is developing a new technology for high-speed metal AM and has raised $5.6 million in funding. Daido Steel has developed a new metal AM powder for making die-casting tools known as LTX.

Obayashi Corp. is developing an automated construction system using a concrete extruder at the end of a robot arm. The National Astronomical Observatory of Japan has made receiver parts for a radio telescope using metal AM. Japanese artist Mago Nagasaka installed a monument known as Moontower at Mago Gallery Shodoshima that is 7.5 m (24.6 ft) in height. Parts for the monument were made using a pellet-fed Chashitsu MEX printer from Slab Corp. The upper sphere consists of 1,022 translucent hexagonal parts, which can be lit up at night. The 5 m (16.4 ft) tall supporting tower was constructed from an assembly of three parts, which were printed in one week.

Fig. 218. Moontower in daytime (left) and at night (right), courtesy of Tatsuya Hama

In-person attendance at industry events increased, including Formnext Forum Tokyo and TCT Japan. Exhibitions that focused mainly on conventional manufacturing also organized AM areas. They included the Japan International Welding Show and the Japan International Machine Tool Fair.

South Korea

by Keun Park

According to Korea's National IT Industry Promotion Agency, the South Korean market for AM systems and services grew to an estimated $422 million in 2022, an increase of 9.2% over 2021. More than 300 AM-related companies are operating in the country. They include 158 service providers, 82 distributors of AM products, 49 system manufacturers, 18 materials producers, and 13 software developers.

InssTek manufactured a nozzle made in functionally graded material for a commercial rocket application. Samyoung Machinery has developed a smart factory solution based on a 3D printer for sand. It includes an automatic powder supply system, an automatic job box conveyor system, and a production control and monitoring system. Metal3D started mass production of a combustion pre-chamber for large ship engines using metal AM.

Fig. 219. Rocket nozzle with functionally graded materials, courtesy of InssTek

In 2022, the Korean government spent $74 million on R&D projects, a decrease of 8.6% compared to 2021. The local government of Ulsan City invested $18 million to establish the 3D Printing Manufacturing Center. The center aims to develop AM technology for the shipbuilding and energy industries.

DN Solutions launched the DVF 8000T-AML, a new hybrid manufacturing system. The 5-axis system combines metal DED and computer numerical control (CNC) machining functions. CS Cam released a large-format PBF system in collaboration with the Korea Atomic Energy Research Institute. Cubicon launched a large-format VPP system with build volume dimensions of 2.0 x 1.0 x 0.7 m (78.7 x 39.4 x 27.6 ft). Carima released the DLP-based IMC system for the 3D printing of ceramics. The Public Procurement Service of Korea selected three AM systems as innovative procurement products for 2022. They were Carima's DM400A DLP-based system and the EP-500 MEX and SL-2300 VPP systems from Lincsolution.

Fig. 220. The DVF 8000T-AML hybrid manufacturing system, courtesy of DN Solutions

Singapore

by Matthew Waterhouse and Ho Chaw Sing

The Singapore AM market grew steadily across all sectors in 2022. An estimated 200 local companies are active in Singapore's AM value chain. Many of them use products and services from about 25% of global AM companies.

MolyWorks opened its first metal powders factory outside the U.S. at the JTC Space @ Gul business park. PrinterPrezz, a U.S. company specializing in 3D printing for the biomedical and aerospace sectors, has set up a Singapore hub. The hub collaborates with spinal and orthopedic specialists from Singapore's national healthcare groups. Working with the National Additive Manufacturing Innovation Cluster, perhaps better known as NAMIC, PrinterPrezz hopes to expand clinical adoption of 3D-printed implants. Singaporean company Osteopore continues to support surgeons around the world performing oral and maxillofacial surgeries. In 2022, the company reached a milestone of supplying 80,000 implants.

The Collins Aerospace Singapore Innovation Hub is one of three company-based global AM R&D centers. It is developing AM materials and technologies needed for lighter, streamlined, and more fuel-efficient aerostructures and related products. Thyssenkrupp and Wilhelmsen Ships Services are partners for the design and on-demand production of 3D-printed marine parts. A range of ship maintenance, repair, and overhaul companies are now designing and 3D printing complex products, such as hulls and propellers, using recycled feedstock.

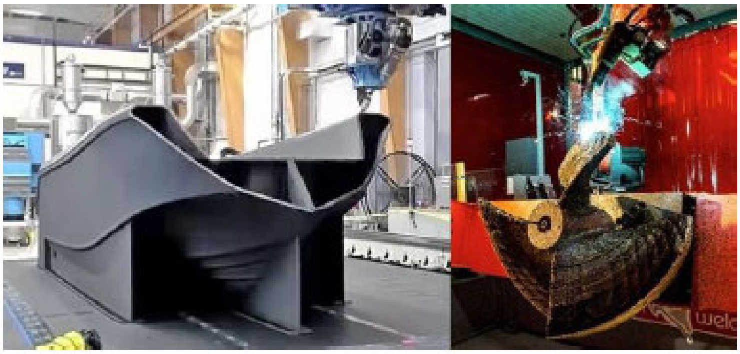


Fig. 221. Patrol boat hull (left) and ship propeller (right), courtesy of the University of Maine and RAMLAB, respectively

CES_INNOFAB is a spinoff from the Chip Eng Seng Group, a Singaporean construction and property conglomerate. The company signed an agreement with Nanyang Technological University (NTU) to lead commercial development and production of sustainable 3D-printed concrete prefabricated bathroom units.

Space technology startup Aliena has partnered with Creatz3D to develop 3D-printed ceramic parts for its satellite propulsion systems. Two metal AM artifacts, designed by Singaporean artist Lakshmi Mohanbabu, are now orbiting the earth on the International Space Station. Both objects are part of the Moon Gallery and were developed as part of a NAMIC-supported partnership with NTU scientists.

Fig. 222. Large 3D-printed artwork cube designed by Singapore artist Lakshmi Mohanbabu and printed, courtesy of NTU

Taiwan

by Jeng-Ywan Jeng

The very strong demand for products from Taiwan's semiconductor industry has led companies in that sector to recruit additional engineers. Consequently, the Taiwan AM industry is facing a major shortage of engineers. Despite ongoing geopolitical and pandemic issues, the Taiwan International 3D Printing Show and Taiwan AM Association activities ran successfully in 2022.

Many companies supporting the AM ecosystem in Taiwan continue to thrive. They include Chung Yo Materials, Circle Metal Powders, Phrozen, Road Ahead, SolidWizard Technology, Tongtai, XYZprinting, and Young Optics. The use of metal AM is growing rapidly, particularly binder jetting (BJT), combined with a sintering process.

Everplast Machinery Co., Ltd., a producer of polymer extrusion machines, has diversified into making 3D printers for concrete structures and large decorative polymer parts. The company's concrete printing system can build parts up to 3 x 3 x 3 m (118 x 118 x 118 in). Three different polymer systems are available, with the largest one having a build volume of 2 x 0.8 x 0.6 m (78.7 x 31.5 x 23.6 in). Large companies are getting involved with AM, including Foxconn, one of the world's largest employers.

Fig. 223. 3D-printed concrete part (left) and large decorative parts (right), courtesy of Everplast Machinery

Design for AM (DfAM) is another growing field in Taiwan, particularly at institutions of higher education including NTUST and Taiwan Tech. Some companies in aerospace, medical devices, and electronic devices are also working in this area. The High Speed 3D Printing Research Center at NTUST has developed and patented novel designs for closed-cell and lattice structures.

Australasia

Australasia includes Australia, New Zealand, New Guinea, and neighboring islands in the Pacific. This region of the world began to use AM technology more than three decades ago.

Australia

by Milan Brandt and Simon Marriott

Even though the pandemic has ended, the AM community in Australia is still facing many challenges. Despite this, AM has shown great resilience and continues to evolve. Major AM companies expanded their activities with a focus on sustainability. Among them are Amaero, Amiga Engineering, AML3D, Conflux Technology, Romar Engineering, SPEE3D, and Titomic.

Conflux Technology received a A$8.5 million ($5.7 million) investment in 2021, which helped expand its activities significantly in 2022. The company announced partnerships with Dallara, General Atomics, GKN Additive, and Mott Corp. Romar Engineering continued its transformation from a prototyping operation to a manufacturing company. Its AM-produced valves for space applications reached an important milestone with a successful test fire. The next step is space flight qualification. Additive Assurance secured A$4.1 million ($2.7 million) in capital through an Australian venture capital fund, which will support the commercialization and sales phases.

SPEE3D opened a new manufacturing facility in Melbourne to support anticipated growth. The company also recruited Paul Maloney, former Desktop Metal vice president of global sales, as its chief sales officer. AML3D secured work with energy, oil, and gas companies. Andy Sales, the company's founder, moved into the CTO role and was replaced as CEO by Ryan Miller.

Fig. 224. High-pressure oil and gas piping component being made using wire-arc AM, courtesy of AML3D

Titomic continues to evolve and has diversified into coatings and repair. The company hired AM industry veterans Neil Matthews and Bruce Colter to lead its repair business and U.S. operations, respectively. It also started joint ventures with Repkon, a Turkish company, and UK-based Nèos International.

The after-effects of the pandemic lockdowns led to the cancelation of all major Australian AM conferences and exhibitions in 2022. Several events are planned to resume in 2023.

New Zealand

by Olaf Diegel

The AM industry in New Zealand has continued its slow but steady growth. Some AM users are moving away from the larger AM vendors, such as 3D Systems, EOS, and Stratasys, toward less well-known system manufacturers. These companies include Eplus3D in China, Photocentric in the UK, and Hontai in Australia. Reliable support and maintenance services are difficult to find locally in the country. New Zealand is believed to be a low priority for many AM system manufacturers, with customer support mostly coming from overseas.

In 2022, AM service provider RAM3D purchased two Renishaw machines, bringing its total to 10 metal AM systems. Another two machines are scheduled for delivery in early 2023. Other systems purchased by service providers included a metal and a polymer system from Eplus3D, at least two Markforged Metal X systems, two HP multi jet fusion (MJF) systems, and several Figure 4 machines from 3D Systems. The metal and polymer AM machines made available after the 2021 closure of the Callaghan Innovation AddLab were acquired by FI Additive. The systems have been put back into production.

After receiving considerable investment in 2021, Foundry Lab launched its AM-based casting system. Molds are printed through BJT. A slug of metal is then melted into the mold in a microwave system. The process was first presented at Formnext 2022 in Frankfurt.

Fig. 225. Cast parts from the Foundry Lab system, courtesy of Foundry Lab

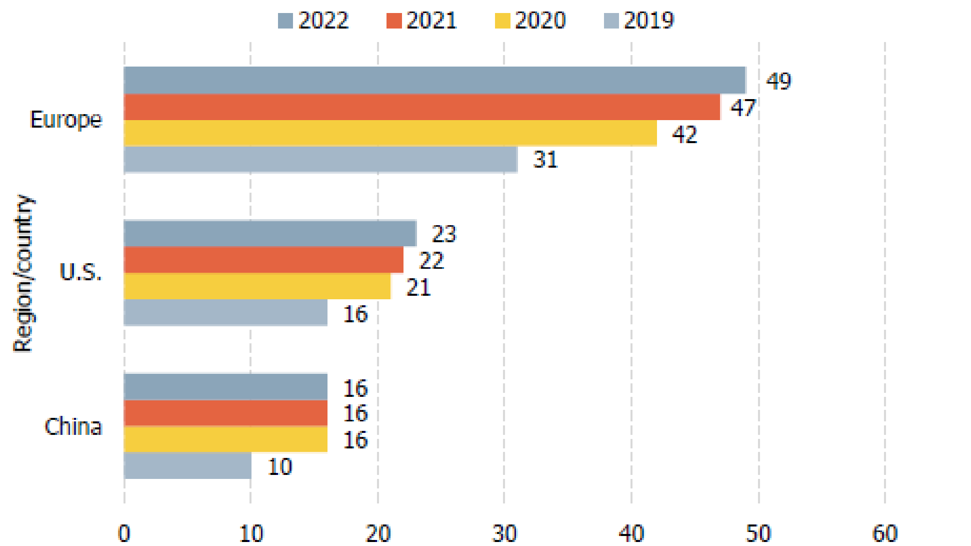
The AM lab at Fisher & Paykel Healthcare has developed ordering and scheduling software. The system supports 24-hour turnaround of nearly all 3D-printed parts.

Europe

As many as 140 manufacturers in Europe produced and sold industrial AM systems in 2022, up from 118 in 2021, 113 in 2020, 95 in 2019, and 69 in 2018.

Europe has a long history of developing metal AM equipment and continues to lead in this area. At the end of 2022, Wohlers Associates found 49 manufacturers in Europe (gray bar in the following graph) that produced and sold metal AM systems. This compares to 47 companies (red bar) in 2021.

Fig. 226. Metal AM system manufacturers; source: Wohlers Associates



Companies in many parts of the world are developing and commercializing metal AM systems. In the U.S., 23 manufacturers commercialized AM systems in 2022, compared to 22 in 2021, 21 in 2020 and 16 in 2019. In China, 16 manufacturers were producing metal AM systems at the end of 2022, no change from 2021 and 2020.

Austria

by Jürgen Stampfl

Austria's AM community is focusing mainly on industrial applications. Austrian manufacturers produce a broad spectrum of 3D printers, together with suitable materials. They range from nanoscale 3D printers to large industrial systems. Almost all companies operate internationally, with typical export rates ranging from 80% to 95% of total production.

Lithoz, a global market and technology leader in ceramic 3D printing, has acquired German company CerAMing. The new acquisition holds a patent for the layer-wise Slurry Deposition ceramic 3D printing process. Lithoz brought to market its Laser-Induced Slipcasting technology. It supports the production of fully dense and large ceramic parts with thick walls.

Eburo, a spinoff from TU Wien, started operations in 2022. It produces 3D-printed parts made from a synthetic ivory material called Digory. With appealing aesthetic properties, Digory can be used for jewelry, interior design products, decoration of musical instruments, and restoration of historical art objects.

Fig. 227. 3D-printed synthetic ivory, courtesy of Eburo

Funded by the Austrian Research Promotion Agency until 2025, the We3D project is seeking to expand applications of wire-arc AM. Ten industrial and five academic partners are developing materials, processes, and applications. Cubicure is offering industrial cleaning solutions and a new range of materials focused on electronic product applications. UpNano successfully completed a funding round with an aim to provide financial backing for its entry into the U.S. market.

Additive Manufacturing Austria (AMA), an AM association with 60 members, represents the interests of the industrial AM community to the federal government. In 2022, AMA started several international initiatives to expand its activities in Europe. The two major AM events in 2022 were the 9th Austrian 3D-printing Forum in Vienna and the Metal Additive Manufacturing Conference 2022 in Graz.

Belgium

by Kris Binion, Olivier Rigo, and Julien Magnien

The Belgian AM landscape went through several interesting and promising evolutions in the recent past. Local demand for AM solutions continues to grow. AM is fast becoming a mainstream manufacturing technology in Belgium.

Research university KU Leuven launched Leuven.AM, a multi-disciplinary AM institute involving 200 experts from throughout the university and university hospitals. In June 2022, the university opened the new Princess Elisabeth AM Lab, further expanding its research capacity. Ghent University and Vrije University Brussels have also expanded their AM R&D activities.

The Flemish regional government invested significantly in AM education, supporting the local public employment service to expand its training offers. Service provider and software producer

Materialise released its CO-AM software platform, further positioning the company as a major player in AM. Other companies, including AdditiveLab, Hybrid Software, Oqton, and Twikit, also offer software solutions for the AM value chain.

Several startups have set themselves apart from others with noteworthy offerings. They include Bio Inx, Carboganic, Colossus Printers, FuseLab, Metal Spark, Sculpman, and ValCun. FuseLab, for example, designed and patented a rotary extruder intended to support metal and ceramic MEX printing. Sculpman has developed a patented extruder that prints ribbons of material in varying sizes.

Companies demonstrating growth include Amnovis, Cerhum, and Guaranteed. Service provider AnyShape is growing continuously and now has seven AM machines. Aerosint was acquired by Desktop Metal.

Aerospace company Sonaca is using wire-arc AM and laser beam welding to produce aerostructures in third-generation Al-Li alloys. Safran Aero Boosters is providing AM parts for the Prometheus rocket engine. Engie Laborelec has initiated qualification of a 350-kg (772-lb) impeller for the energy sector. It was produced by MX3D, an AM company in the Netherlands.

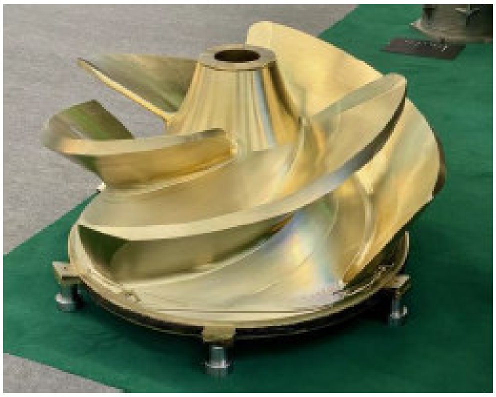


Fig. 228. Large-scale impeller for the energy sector, courtesy of MX3D

Czech Republic

by Kateřina Podaná and Michal Zemko

The Czech Technology Platform for Additive Manufacturing partnered with ASTM International to create and publish the first Czech roadmap for AM. It reflects important input gathered from academia and industry. It is the first strategic document produced specifically for the AM industry in the Czech Republic. It is being used by companies, universities, and government departments to further develop the country's AM industry. Download the roadmap at www.ctpav.tech.

The Czech government has integrated AM explicitly into the Research & Innovations Strategy public documents at both national and regional levels. This will help encourage public support for targeted projects and startups. Major AM research centers at several Czech locations are covering construction, healthcare, energy, tooling, defense, and automotive. Extensive cooperation between research centers is expected in future years.

The So Concrete company designed a tram stop shelter using artificial intelligence, with sections being 3D printed. The design used principles of biomimicry to optimize the distribution of pressure and tensile stress within the roof structure. The completed shelter was erected in Prague in July 2022.

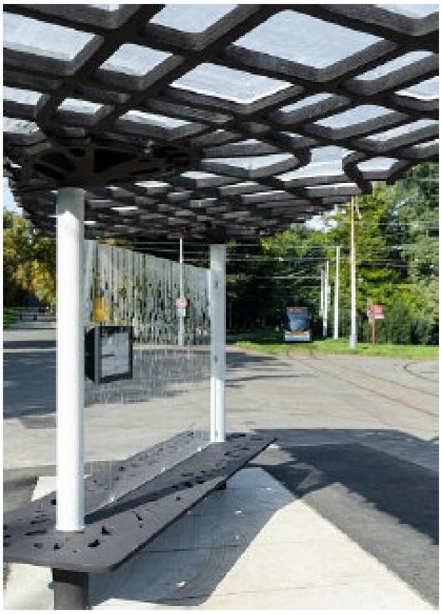


Fig. 229. 3D-printed section of a tram stop shelter, courtesy of So Concrete

The Czech Republic is home to Pruša, a manufacturer of desktop 3D printers. Until recently, Pruša has mainly specialized in making systems for hobbyists and small businesses. The company has launched the Automated Farm System, a scalable print farm with print job management and automatic harvesting of finished prints.

Several companies in the Czech Republic produce various MEX filaments from basic and advanced materials, including NonOilen biodegradable PLA from Fillamentum. Some startup companies are focusing efforts on 3D printer components such as nozzles.

AM is now a topic at several conferences held regularly in the Czech Republic, including COMAT. A new conference called NEXT3D was held for the first time in May 2022. It was aimed at a wide audience that included beginners and advanced users of AM for polymers, composites, and metals. The Additive Manufacturing Forum, held in October 2022, focused on how 3D printing fits within the context of conventional manufacturing.

Denmark

by Steffen Schmidt

Denmark continues to embrace AM and sustainable manufacturing. According to the Danish AM Report 2022, one-third of Danish manufacturing companies used AM technology in 2021. About 20% of these companies are focusing on sustainability, using AM technology to develop more sustainable production and products.

Nordic Metals has developed a new stainless steel powder for 3D printing known as 440C. The metal is also available in solid billets to support use in hybrid manufacturing processes, in which both subtractive and additive processing are used.

Wohn Homes A/S is now ready to start production of small, affordable housing modules of 20 m^2 (215 ft^2) in size. The goal is to make construction more sustainable by building with recycled polypropylene and waste wood fibers. Each house uses up to four tons of waste, reducing the carbon footprint by more than 90%, compared to similar homes made of concrete and steel.

The Danish AM Hub is funding development of a carbon footprint/CO2e calculator. It will give decision makers a tool to help choose the most sustainable manufacturing processes. The calculator helps manufacturers and suppliers compare their conventional manufacturing processes with AM alternatives.

Classes on AM and related topics are now offered for many skillsets and levels, from basic AM operator to master of technology management with AM as a specialty. AM Summit 2022, the largest AM conference in Scandinavia, attained record attendance. More than 450 participants, 45 exhibitors, and 40 speakers came together to learn more about AM as a driver for sustainable manufacturing.

Finland

by Mika Slami

Finnish manufacturers are increasing their use of AM as a production method. Service providers have invested in new metal and polymer 3D printers. Swedish service provider Amexci has expanded in Finland with a new site at Tampere.

The largest AM company in Finland, EOS Finland Oy, launched new materials that include EOS-branded products named StainlessSteel SuperDuplex, ToolSteel CM55, and NickelAlloy Haynes 282. The company also launched a high-productivity 80 µm process for Inconel 718 and support-free processing of 316L stainless steel. EOS Finland Oy also won the 2022 Finnish 3D

Printing award, presented by the Finnish Rapid Prototyping Association (FIRPA). FIRPA, founded in 1998, promotes AM activity and acts as an independent source and national resource for AM information.

Finland achieved a first for the nuclear power industry when 3D-printed filters were given regulatory approval. The Olkiluota nuclear power plant loaded two fuel assemblies equipped with the filters, which are used to exclude foreign material in the reactor.

Andritz Savonlinna Works Oy and the Finnish Additive Manufacturing Ecosystem (FAME) demonstrated printing of a pressure vessel using DED that is 1.6 m (63 in) in height. FAME also launched a €6-million DREAMS project in 2022 focused on building a database for enhancing AM and standardization. Business Finland and partner companies are funding the project.

Fig. 230. Demonstration build of a 360-kg (794-lb) pressure vessel made in 316L using wire-based DED, courtesy of Andritz Savonlinna Works Oy

Hyperion Robotics specializes in the 3D printing of cylindrical storage structures. The company raised €3 million in a funding round and won the Proptech Startup & Scale-up Europe Award. Bioprinter manufacturer Brinter launched the first multi-material, multifluid printhead for 3D bioprinting. MiniFactory released the Ultra 2 printer for producing high-performance polymers and composites.

Fig. 231. Liquid container 2 m diameter x 2 m in height 3D printed from geopolymer waste in 90 minutes, courtesy of Hyperion Robotics

France

by Benoit Verquin

AM continues its expansion into final part production in many sectors and is no longer used only for high-value applications. More large metal AM parts are being produced in industry, driven mainly by wire-arc AM technology.

EDF, the multinational electric utility company, is investigating AM for spare part production. Framatome, an international leader in nuclear energy, has installed the first stainless steel AM fuel assembly part at the Forsmark Nuclear Power Plant. The Atrium 11 upper tie plate grid shown in the following is a weight-bearing part. It secures fuel rods and stops debris from falling into the fuel assembly.

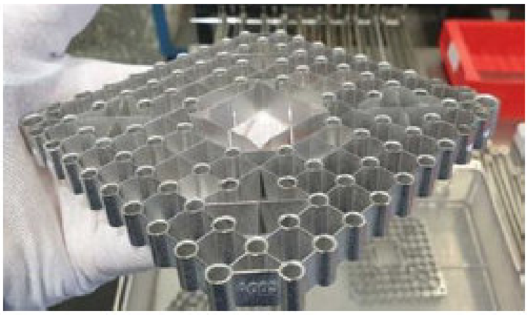


Fig. 232. 3D-printed Atrium 11 upper tie plate grid, courtesy of Framatome

The Safran Group has opened the Safran Additive Manufacturing Campus (SAMC), a new center of excellence in Le Haillan, near Bordeaux. The 12,500-m² (134,550-ft²) facility houses more than 100 scientists, engineers, and technicians responsible for producing parts for the organization. SAMC delivered 4,000 parts in 2022 and is expected to double that figure in 2023.

Vallourec completed a wire-arc AM production of a sealing ring to be used by EDF Hydro in its hydroelectric installations. The safety-critical component is made from martensitic stainless steel, has a diameter of 1 m (39.4 in), and weighs about 100 kg (220 lbs). Irepa Laser successfully produced a large rotomolding tool using a wire-fed laser DED system. It took 16.5 days to build in 316L stainless steel using the company's large dual-robot DED cell. The part measures 2.2 m (7.2 ft) in diameter and weighs 1,200 kg (2,646 lbs).

Fig. 233. Rotomolding tool made using wire-fed laser DED, courtesy of Irepa Laser

Schneider Electric has developed AM-produced filters for NSX circuit breakers. The filter design reduces exhaust gas pressure and the amount of heat produced in a confined space, resulting in significant environmental benefits. The filters were produced in partnership with HP and GKN using a metal BJT system.

Institut de Soudure helped cavity pump manufacturer PCM to develop wire-arc AM processes for its range of rotors and stators. Using AM helped PCM simplify its material range, significantly reduce the mass, and improve pumping efficiency by 30%.

Fig. 234. Pump parts produced using wire-arc AM (left) and after finishing (right), courtesy of Institut de Soudure

Startup La Pâtisserie Numérique has developed a pastry 3D printer that allows chefs to automate the production of cookies. The machine will be commercialized in 2023.

Fig. 235. Pastry 3D printer (left) and example cookies (right), courtesy of La Pâtisserie Numérique

Several leading French R&D and technology transfer centers organized a new metal AM event at Cetim (a national technical center for mechanical industries) near Paris. It is called the Metal AMS symposium and was run by members of the National Cohesion on Metal AM network. The France Additive association celebrated its 30th anniversary. It has 180 members representing the French AM community.

Germany

by Sebastian Piegert and Christian Seidel

After two difficult years, AM activities in Germany are recovering well from the impact of the pandemic. Attendee numbers at three major AM events (AM Forum, Formnext, and Rapid.Tech) nearly reached pre-pandemic levels. Many conferences are still operating in a hybrid format, but most participants are attending in person. AM sustainability was a theme of panel discussions and dedicated sessions at the AM Technology Conference and the Seminar für Additive Fertigung.

SLM Solutions introduced an extended version of the NXG XII 600 system with a *z* axis of 1.5 m (59 in). The company also announced a new machine concept with a build volume of 3.0 x 1.2 x 1.2 m (118.0 x 47.2 x 47.2 in). ALD Vacuum Technologies introduced a PBF machine with a build volume of 0.85 x 0.85 x 1.0 m (33.5 x 33.5 x 39.4 in) and a 150-kV electron beam gun from Pro-beam.

Two new platforms for AM services were launched. MakerVerse is a joint venture between Siemens Energy, Zeiss, 9.5 Ventures, and other venture capital funds. EOS launched the End-To-End Production Network designed to connect companies of all sizes in the AM market. Major market consolidations included Nikon acquiring SLM Solutions, 3D Systems buying dp polar, and Multiphoton Optics becoming a branch of Heidelberg Instruments.

AIM3D announced its Voxelfill technology, which is designed to produce polymer parts with increased isotropic properties. Apium Additive Technologies released the Apium P400 system with adaptive heating. The company claims the process improves inter-layer adhesion for high-performance MEX materials such as PEEK.

Trumpf updated its range of laser PBF machines. The TruPrint 1000 is targeted at serial production and includes dual lasers and multiplate technology. The TruPrint 3000 has two 700-watt lasers, and the TruPrint 5000 Green Edition uses green laser light to process pure copper. DMG Mori introduced blue lasers for its hybrid DED machines to improve energy absorption when processing copper.

Fig. 236. TruPrint 1000 machine for serial production, courtesy of Trumpf

Fraunhofer IGCV completed a $21-million project titled Multi-material Center Augsburg in March 2023. It presented example applications from the aerospace, energy, and tooling industries to demonstrate 3D-printed multi-material parts. An injection-molding tool insert was produced with algorithm-based material distribution and an embedded temperature sensor for improved process control.

Fig. 237. Multi-material injection-molding tool insert with embedded temperature sensor, courtesy of Fraunhofer IGCV

The Academic Network Munich for Additive Manufacturing received funding for five AM-specific professorships at three Munich-based universities. The Werner von Siemens initiative in Berlin launched several AM projects focusing on high-temperature applications as well as maintenance, repair, and overhaul. The partners include Fraunhofer, the Federal Institute for Materials Research and Testing, the Technical University of Berlin, and Siemens and Siemens Energy.

The Technical University of Munich is continuing its EU-funded research on the benefits of using AM for fuel cells. The university also received Horizon Europe funding for the DISCO 2030 project, planned to run until 2025. The project focuses on making parts from dissimilar materials (i.e., different metals or metals with polymers using a combination of AM processes).

Ruhr-University Bochum expanded its capacity for metal and polymer AM research by opening the Research Center for the Engineering of Smart Product-Service Systems. The University of Duisburg–Essen continues its research on titanium-based metallic glass produced using laser PBF of metals. RWTH Aachen extended its research on AM process chains through the project HIGHRES. The project is focused on processing low-cost steel using AM and hot isostatic pressing. The University of the Armed Forces, Munich opened a cross-departmental research lab dedicated to AM research covering polymers, metals, ceramics, and composites.

Greece

by Andrew Triantaphyllou

Polymer AM is established in dental labs and in the jewelry sector. Jewelry company Kranias Astroroes is an example. Service providers are reporting increased revenue as other sectors begin to embrace AM.

Several companies now use polymer AM tools instead of conventional tooling. They include a furniture manufacturer, an electrical hardware producer, and a window system manufacturer, which also supplies polyamide AM fittings. In the boating industry, Stefos Yacht Services uses a Massivit 1800 system to make mold tools and end-use parts.

Interest in metal AM is growing, such as for making repairs in the shipbuilding sector, though certification is currently a challenge. Metal AM systems are installed in several research labs. The Laboratory of Machine Elements and Machine Design at the Aristotle University of Thessaloniki has an EOSINT M 280 system. The Laboratory for Manufacturing Systems and Automation at the University of Patras has a robotic cell for hybrid processing. The Technical University of Crete has a DED system from Meltio. AM solutions provider Conify has a Meltio M450 machine and an iFusion SF1 PBF system from Intech.

The government of Greece actively encourages AM adoption. The General Secretariat for Research and Innovation, with support from the EU, has established two new AM competence centers. The Hellenic Centre of Excellence for AM has a focus on high-performance polymers. The I4byDesign competence center focuses on Industry 4.0 and has AM systems for building polymer, carbon composite, and ceramic parts. The centers complement the existing Additive Manufacturing Unit at the Centre for Research & Technology Hellas, which has metal, polymer, ceramic, and bioprinting equipment.

Several universities offer degree courses that include AM modules. Among the institutions are the National Technical University of Athens, the National and Kapodistrian University of Athens, and the University of Patras. They leverage AM research to support teaching and, in some cases, partner with local service providers to include industry insight. A Greek AM association, AM4GR, has been established by FEAC Engineering, Siemens, Demokritos, and Elkeme.

Italy

by Michele Pressacco, Elisa Salatin, and Riccardo Toninato

Most major industry sectors are recovering well from the disruption caused by the pandemic. Investments related to the aerospace sector have grown significantly.

Avio Aero and BEAMIT are using GE Additive's Concept Laser M Line to produce parts for the GE Catalyst turboprop engine. Lincotek Medical installed an EOS M 300-4 machine in its Additive Innovation Centre. Racing bicycle specialist Pinarello released the Bolide F HR 3D model, featuring a Scalmalloy frame built on an EOS M 400 machine. The frame was designed in collaboration with professional cyclist Filippo Ganna and the Ineos Grenadiers racing team.

Mimete, a member of the Fomas Group, together with Punch Torino and CDP Venture Capital, announced the establishment of MadeInAdd. The company is introducing a new digital model for the design and production of 3D-printed parts. Prima Industrie announced it had completed the spinoff of its AM business unit, following a merger with 3D New Technologies. The newly formed company, Prima Additive, launched a robotic laser DED cell at Formnext 2022. Roboze became a partner in the CIM4.0 national competence center. The center aims to support manufacturing companies moving into the digital age and adopting Industry 4.0.

HP and Legor Group announced a strategic collaboration to develop precious metal material systems for HP's MJF platform. The materials focus on the jewelry and fashion markets. Thales Alenia Space signed an agreement with aerospace component manufacturer Miprons to develop a satellite propulsion system using water as a fuel. The system will feature AM parts.

The Italian government launched a multi-million euro call for industrial and academic projects to support the country's economic recovery. The call is part of the Piano Nazionale di Ripresa e Resilienza, which leverages EU funding. Project topics include development of a national innovation ecosystem, economic growth enhancement, and implementation of AM.

Netherlands

by Joris Peels

3D printer manufacturer Ultimaker merged with MakerBot. The combination of resources and market share makes it a leader in the desktop 3D printer market. Optical lens firm Luxexcel was bought by Facebook parent Meta and is 3D printing prescription augmented reality (AR) and virtual reality (VR) glasses. Dutch chemicals and nutrition firm DSM sold its AM business to Stratasys. Dutch companies Admatec Europe and Formatec were bought by Israeli firm Nano Dimension. Together with previous international acquisitions of 3D Hubs, Dutch Filaments, and Innofil3D, the Dutch AM ecosystem has diminished.

Weber Beamix is industrializing the mass customization of 3D-printed concrete for flights of stairs, bridges, and even parts of homes. The stairs are reportedly one-third less expensive than conventionally manufactured units. They can be configured online, delivered in two weeks, and said to comply with local building regulations. MX3D has manufactured large oil and gas components and art installations using wire-arc AM. 3D4Makers introduced an extremely high-strength polyamide filament, claimed to outperform PEEK and PEI.

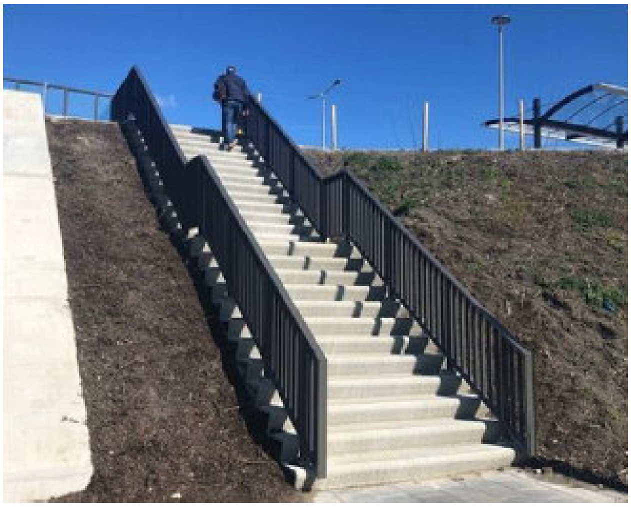


Fig. 238. 3D-printed concrete stairs, courtesy of Weber Beamix

The 3D Concrete Printing research group at Eindhoven University of Technology is offering master's- and doctorate-level projects in collaboration with industrial partners. Research themes include artificial intelligence (AI) in construction, functional and sustainable materials, reinforcement strategies, and structural optimization. In June 2022, Additive Industries announced a three-year extension of its technology partnership with Sauber Technologies and Alpha Romeo F1 racing team Orlen.

Norway

by Klas Boivie

The AM industry in Norway continues to make progress, led by energy and shipping companies. Both sectors share common goals of shortening supply chains and accessing spare parts on demand.

Startup company Fieldnode is partnering with Norwegian energy industry leader Equinor, together with ConocoPhillips, Shell, TotalEnergies, and Vår Energi. The partnership has developed the Fieldnode Platform, a digital foundation for a network-based supply of on-demand spare parts produced using AM. Mobile AM production specialist Fieldmade AS provided Equinor with a production module for use at the Johan Castberg oil field. As of February 2023, more than 1,300 AM components had been produced on-site.

Wilhelmsen Ships Service is working with the Norwegian-American Ivaldi Group to digitalize its spare parts supply service. Parts are prequalified, tested, certified, and then added to a digital warehouse. The goal is to create a system where digital files can be sent for local, on-demand production using AM.

Visitech, a supplier of DLP light engines and subsystems, has delivered more than 2,000 UV-based solutions to the AM industry since 2011. In November 2022, the company released Direct Image Sintering, an IR-based solution for PBF processes. The combination of DLP and IR supports instant exposure, coupled with high precision and resolution, according to the company. Visitech has also developed a scrolling system in which the DLP units move across the build area. This technology can be scaled for application to large build volumes.

In July 2022, the Norwegian AM Cluster (NAMC) was officially formed to serve as a national network for AM stakeholders. It aims to promote efficient and sustainable use of AM technologies, spread knowledge, and support research and education. Starting in 2023, NAMC is organizing an annual national AM conference.

Poland

by Kinga Skrzek

The AM industry in Poland is developing dynamically. More companies are discovering new and interesting ways to use this technology. Despite economic problems, more manufacturing companies have decided to implement AM to keep their production lines running smoothly.

Polish startup Wimba makes orthoses and prostheses for dogs using 3D printing. Using a new measurement technique and specialized AI software, the limbs of dogs are measured to an accuracy of 0.4 mm (0.016 in). Level2 Ventures provided Wimba with funding of PLN 4 million ($903,000) for continued development.

The Ministry of Education and Science, in cooperation with the GovTech Center at the Chancellery of the Prime Minister, provided more than PLN 1 billion ($226 million) to create laboratories in Polish primary schools. As part of the Laboratories of the Future program, over 13,000 3D printers were delivered to Polish schools. The program aims to build future competencies among students enrolled in science, technology, engineering, art, and mathematics (STEAM) as a major.

In April 2022, the annual 3D Printing Days event was held in Kielce. It is the largest AM show in Poland. The show attracted an increased number of 3D printing companies. Representatives from the 3D scanning industry and companies in other AM-related sectors participated in the fair. Many examples of interesting 3D printing applications were on display.

Fig. 239. 3D-printed life-size model of a running man (left) and an electric guitar with a 3D-printed body (right), courtesy of Kinga Skrzek

The conference Rapid Prototyping – 3D & 4D Printing in Engineering Applications took place for the fifth time in September 2022. A key focus was the use of AM for production applications. Research in the field of 4D printing was presented.

Portugal

by Joel Vasco and Henrique Almeida

Portuguese automotive OEMs and Tier 1 suppliers are showing increased interest in AM. Significant investments are being made in polymer AM processes by companies including Aptiv, Faurecia, and Yazaki. Companies in the dental, footwear, and aerospace sectors have made further investments in metal AM systems.

The School of Technology and Management at the Polytechnic Institute of Leiria is launching the Direct Digital Manufacturing Laboratory in Q2 2023. The lab will host a wide variety of processes, including AM, milling/cutting, formative manufacturing, reverse engineering, robotics, and virtual/augmented reality. The facility will be used to support undergraduate, master's and PhD programs. Partnerships with AM stakeholders are also under development.

As part of its mobilizing agenda for economic recovery, the Portuguese government has approved the INOV.AM project. It involves 67 companies, seven R&D organizations, and four industrial associations. INOV.AM began in October 2022 with 24 subprojects focused on mold tooling, AM equipment and materials, hybrid manufacturing, AM training, and software development. The project is expected to have a positive impact on several sectors, including construction, furniture, transportation, healthcare, and food. Engineering solutions provider Erofio is the lead organization for INOV.AM. The company has extensive knowledge in optimizing molds. It uses in-house metal PBF equipment to create molds with differentiated thermal control, which shortens cycle times and improves part quality.

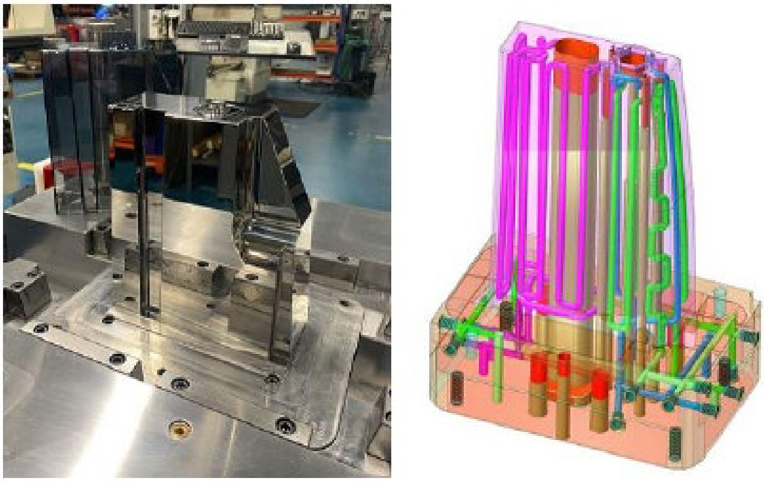


Fig. 240. Mold produced using metal PBF (left) with CAD image showing conformal cooling channels (right), courtesy of Erofio

The biennial conference, Progress in Digital and Physical Manufacturing (ProDPM), is scheduled for October 2023. The School of Technology and Management at the Polytechnic Institute of Leiria will host the event.

Romania

by Nicolae Balc

Following the stagnation from the pandemic, the Romanian AM market grew in the second half of 2022. New AM equipment was installed at universities and industrial companies. Multi-material anatomical models for medical students were built using a Stratasys J55 Prime system. AM service providers are producing parts using a wide range of AM systems including fused deposition modeling (FDM) from Stratasys, stereolithography from 3D Systems, and machines from Ultimaker and Anycubic.

AM system distributor CAD-Works expanded its offering after Markforged acquired Digital Metal. Sales of Ultimaker systems increased after the company merged with MakerBot. The national project "Digitalization of Romania" has provided funding to purchase 3D printers.

The European Space Agency funded AM research projects at COMOTI, the Romanian R&D Institute for Gas Turbines, and the aerospace company HPS. COMOTI is developing AM parts for space vehicle centrifugal pumps, including closed impellers and pump housings. As part of the 3D-SAMER project, HPS is developing an antenna system with a support structure made using AM.

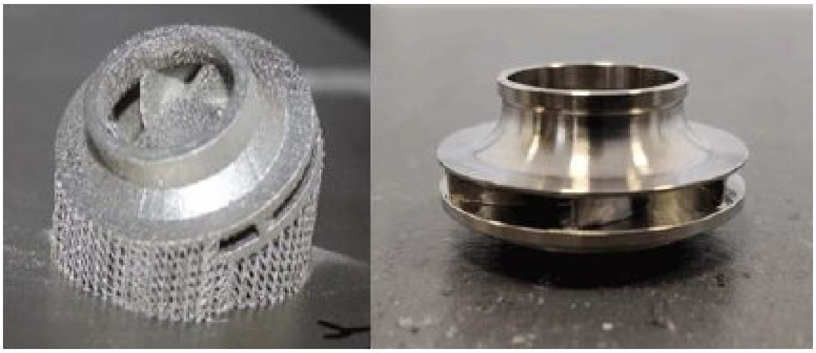


Fig. 241. As built impeller made using PBF (left) and after finishing (right), courtesy of COMOTI

The Transylvania University of Brasov has developed an unmanned aerial vehicle that has passed both ground and flight tests. Composite material structural components were made using MEX, and engine parts were produced using laser PBF. Its maximum take-off weight is 11 kg (24.3 lbs). The Technical University of Cluj-Napoca started a new project titled EMERALD. It is a networking project focused on 3D printing of biomimetic mechatronic systems. It involves industry and academic partners from Norway, Poland, Romania, and Slovakia.

Symme3D produces a range of industrial AM systems and is now developing equipment for medical applications. The Symme3D Biotech One system has a temperature- and humidity-controlled incubator, which supports 3D printing using live stem cells.

The International Congress on 3D Printing Technologies and Digital Industry was organized by the University Polytechnic of Bucharest in November 2022. Distributors and universities organized open house events that present new AM technologies and applications.

Slovenia

by Igor Drstvenšek

Increased awareness of AM developments in Slovenia is driving a steady increase in adoption, especially for R&D. Every major company in Slovenia has adopted at least one AM system to support product development and/or maintenance. The country is also experiencing an increase in the number of local manufacturers and distributors of AM equipment.

Startup NPPower launched the Malachite system, its first laser PBF machine for metals, at Formnext 2022. The machine features a 200-watt laser and a cylindrical build chamber with a diameter of 125 mm (4.9 in) and height of 100 mm (3.9 in). The development of the Malachite system was supported by German company Scheftner Dental Alloys, which holds a 26% stake in NPPower.

Fig. 242. Malachite laser PBF system for metals, courtesy of NPPower

A major public R&D investment from the EU Cohesion Fund was completed in 2022. It supported the purchase of new electron-beam and laser PBF systems for the Additive Manufacturing Laboratory at the University of Maribor. The Slovenian Research Agency has launched a research project on biofunctionalization of 3D-printed metal alloys to reduce undesired effects in orthopedic implants. It focuses on the production of patient-specific medical devices with additional pharmaceutical functions. One way to achieve this is to apply a coating on the implant that contains painkillers, antibiotics, or osteoclast inhibitors. Another technique is on-demand delivery of drugs to the implant/bone interface.

CAESS launched version 6.2 of its topology optimization software ProTOp. The company also expanded its distribution network into the U.S. and South American markets. Sandblasting equipment manufacturer FerroECOBlast introduced its new AddiBlast product line at Formnext 2022. Products in the line include machines for manual and automated depowdering of AM parts, surface treatment, and automated powder recovery and conditioning.

Spain

by Naiara Zubizarreta

After two difficult years, the AM market in Spain is once again expanding at a pre-pandemic rate, with many companies reporting strong growth. A growing number of large companies in Spain are beginning to use AM technologies. They include Airbus, ArcelorMittal, Ferrovial, Ford, Grupo CAF, ITP Aero, Navantia, Podoactiva, Seat, Valeo, and Volkswagen.

ADDIT3D, Spain's most important AM trade show, returned to a similar size and number of attendees as before the pandemic. The show was held in conjunction with the BIEMH trade show, with nearly 40,000 visitors. National awards for innovation in advanced manufacturing were presented. Navantia was awarded first prize in the AM category for a hybrid rudder blade produced using large-format AM. The next ADDIT3D is planned for June 2023 in Bilbao.

Fig. 243. Hybrid rudder blade produced using large-format AM, courtesy of Navantia

Podoactiva is producing personalized foot insoles on an industrial scale using AM systems from HP. Many startups have emerged to serve the Spanish AM market. They include 3D printer manufacturer Moso 3D, and two 3D printing materials vendors, Blesol Tech and Eolas Prints. They and several other startups have joined ADDIMAT, the Spanish AM association, bringing the total number of members to more than 110.

Recently, ADDIMAT launched a study to identify the main challenges facing the Spanish AM industry. The goal is to support coordination of measures to help accelerate future growth across Spain.

Sweden

by Seyed Hosseini

Funding for AM development continues within the Swedish innovation system. Many companies, both large OEMs and SMEs, now have a greater awareness of AM benefits. This has resulted in a focus on finding applications of AM that are a good fit.

Most companies using AM are seeking to develop business cases that justify upscaling beyond prototyping or low-volume production. Many metal powder suppliers are adding new materials to their portfolios. Ramén Valves, a small company, has spent several years preparing for AM part production using Ti-6Al-4V. Working closely with AIM Sweden, the company now produces industrial valves using electron-beam PBF.

Fig. 244. Industrial valve made using electron-beam PBF, courtesy of Ramén Valves

The Application Center for Additive Manufacturing is operated by state-owned Research Institutes of Sweden. The growing center has received regional funding from Västra Götalandsregionen, and two new industrial partners have joined. Hexagon AB has brought expertise in digital thread capabilities and Quintus Technologies AB brings competence in heat treatment and hot isostatic processing. The center has reactivated the Additive Intelligence 4.0 Conference, which brings together many industrial stakeholders to discuss future AM trends in Sweden.

Several universities have received public funding to establish undergraduate and graduate modules and entire programs focused on AM. Karlstad University, Mid Sweden University, and Örebro University have jointly developed a master's program dedicated to AM. The EIT RawMaterials initiative at Luleå University of Technology received funding to develop novel flexible membranes using a new metal BJT process.

Visualization company Interspectral has partnered with French AM machine maker AddUp to focus on quality assurance and in-situ monitoring. Markforged expanded its portfolio to include metal BJT through its acquisition of Swedish company Digital Metal. In October 2022, GKN Aerospace acquired Permanova Lasersystem, a Swedish manufacturer of wire-fed DED systems. Freemelt has expanded its offering to include the eMELT industrial AM system.

Switzerland

by Marco Salvisberg

Despite difficult conditions, the AM industry in Switzerland came through the pandemic well, with continued growth. Large industrial companies, such as ABB, GF Casting Solutions, MAN Energy Solutions, and Sulzer, are expanding their services and applications portfolios. Small- and medium-sized service providers are developing into a robust network that is helping to expand the use of AM technology. The Swiss startup landscape is particularly vibrant.

9T Labs completed a $17 million Series A funding round in 2022. Customers are already using 9T Labs' "Additive Fusion" carbon composite manufacturing technology, a two-step process that adds pressure and heat to the built parts. Customers include Fortune 500 aerospace companies and medical corporations. The Zurich-based startup will use the funding to commercialize its Red Series software tools, 3D printer, and molding equipment.

Fig. 245. Red Series build module (left) and fusion module (right), courtesy of 9T Labs

Intelsat became the first commercial customer for Swissto12's innovative HummingSat geostationary telecommunications satellite. The satellite was developed using Swissto12's patented 3D printing technology in collaboration with the European Space Agency.

Startup NematX is pioneering the use of liquid crystal polymers for 3D printing. The company claims its process can achieve precision and performance levels required for high-end industrial production. Another startup, Scrona, received a $9.6 million investment in 2022. The company wants to revolutionize ultra-high-resolution 3D printing for a wide range of industries, including the manufacture of semiconductors and displays.

Turkey

by Burak Pekcan

The AM market continues to expand in Turkey, particularly in the dental, jewelry, and defense sectors. Most of the country's EU-funded projects have been completed and are starting to impact the AM community.

The AMCTURKEY international AM conference, organized by the Turkish Additive Manufacturing Association (TAMA), took place in October 2022 in Kusadasi. This was the third time for the conference, and it attracted more than 250 participants and 22 companies. TAMA also organized online AM Project Days in September 2022 to cover current AM-related R&D projects in Turkey.

More than 90 companies co-sponsored the Turkish AM Industry Survey 2022. Over 200 active AM users from 146 industrial companies and organizations participated. One key finding was that AM is still being used mainly for prototyping and R&D. However, jigs, fixtures, and end-use parts have also become major applications. Another key finding was that knowledge and budget are the main factors limiting growth of AM. Half the participants believed AM will be a "must-have" technology in the next five years.

The ADDress for Future project was launched in July 2022. This project aims to raise AM awareness among engineers, students, academics, and government bodies. It also focuses on promoting AM to the wider business world by bringing together entrepreneurs on a common platform. The project is coordinated by the Coskunoz Education Foundation based in Bursa. Project partners include the European Powder Metallurgy Association, Gazi University, and infoTRON.

Sciaky has announced the delivery of what it believes is the world's largest metal electron-beam DED machine to Turkish Aerospace. The custom EBAM 300 system can build titanium aerostructures up to 6 m (19.7 ft) in length. Startup Co Print raised over $1 million through crowdfunding. Co Print offers a multi-filament module that supports seven different materials in a single build on standard MEX systems.

Sintertek, based in Istanbul, launched the Sinterjet M60 metal BJT system at Formnext 2022. MetalWorm, a spinoff of Intecro Robotics, launched the MHTTN1000, the company's first wire-arc AM system. MetalWorm displayed the new machine at Formnext. Xometry bought a majority stake in Tridi, an on-demand custom manufacturing platform based in Istanbul.

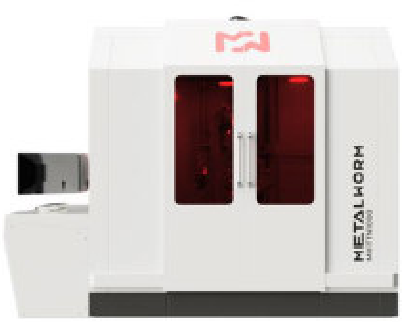


Fig. 246. MHTTN1000 wire-arc AM system, courtesy of MetalWorm

United Kingdom

by Hoda Amel and David Wimpenny

The five-day MACH 2022 exhibition, with a dedicated AM zone, was held in Birmingham in April 2022. This was the first time the biannual show had run since 2018 because of COVID-19 restrictions. The event is the UK's largest manufacturing technology exhibition, attracting more than 25,000 visitors. MACH is produced by the Manufacturing Technology Association, which recently took over responsibility from AMUK, the UK's AM association. The show provided a platform for relaunching the association. In June 2022, thousands of visitors and 160 exhibitors attended TCT 3Sixty 2022, also in Birmingham.

WAAM3D, a spinoff from Cranfield University, launched the RoboWAAM Advanced wire-arc AM system. The system features enhanced automation for fume management, atmosphere control, process monitoring and control, and wire feeding. The hardware unit is complemented by an updated suite of deposition planning and control software. As of January 2023, WAAM3D has shipped 16 deposition systems since 2020.

Fig. 247. RoboWAAM Advanced wire-arc AM system, courtesy of WAAM3D

Nikon Corp. announced an investment in Hybrid Manufacturing Technology. The company's patented AMBIT changeable tool approach supports the integration of a metal AM deposition head into a wide range of machine tool and automation platforms. The investment is one part of Nikon's Next Generation Project, which includes the purchase of SLM Solutions and aerospace AM parts supplier Morf3D.

Wayland Additive has shipped its first two Calibur3 electron-beam PBF machines to be used in production environments. One was sent to the Royal Air Force in the UK, and the other to Exergy Solutions in Canada. Processing of pure tungsten has been a particular focus of recent development work at Wayland, along with other difficult-to-process high-temperature materials.

London startup Ai Build offers programming and control software for large polymer extrusion and metal DED systems. The latest version of its AiSync software offers a range of innovative features. They include real-time print monitoring, automatic build recommendations, and automatic adaption of printing parameters. In 2022, the company was awarded UK government funding to accelerate development of machine learning for live error detection of laser PBF processes. The funding was received in partnership with fluid systems company Domin Fluid Power of Bristol, UK. Ai Build is working with the UK's National Composites Centre to improve the thermal dimensional stability of 3D-printed autoclave tools for composite aerospace parts.

Middle East

by Fahmi Al-Shawwa

Companies in the Middle East have varied attitudes toward the adoption of AM. Most continue to view AM as a novelty, with use limited to model making and simple prototyping. However, many pilot projects are taking place across the region. Etihad Airlines, Dubai Electricity and Water Authority, Aramco, KNPC, Al Seer Marine, and several defense companies have launched proof-of-concept projects.

A noticeable shift in attitudes has occurred in the United Arab Emirates (UAE) and Saudi Arabia. Government enterprises and some larger private organizations are actively exploring the use of AM for functional parts. This significant development will likely reap a few early adopters in 2023 in high-value and industrial applications. The success level of these early adopters will determine how quickly AM will grow in the future in the region.

AM unit sales rose significantly in 2022. Most interest came from dental, jewelry, and model-making companies, as well as academic institutions. The most commonly purchased processes were MJF from HP, ProJet CJP from 3D Systems, and various VPP systems. Interest in metal systems increased in the last six months of 2022.

The Middle East AM ecosystem is heavily dominated by governments and government-related enterprises. The Saudi Arabian Industrial Investments Company (Dussur) announced $100 million in funding for a joint venture with 3D Systems. The goal is to launch a large-scale AM service provider in Saudi Arabia. UAE company Falcon Technologies International has opened a service bureau affiliated with the local government in Ras Al Khaimah. It offers AM services to the medical, oil and gas, defense, and consumer products sectors. Eon Dental of Jordan raised $26 million from venture funding. Dubai-based Immensa, with offices across the region, raised $7 million from strategic investors.

Saudi Arabia and the UAE are taking markedly different approaches to their AM initiatives. In the UAE, AM has been heavily centered in Dubai, with a focus on the construction sector and concrete 3D printing. In Saudi Arabia, the push has been toward industrial applications and the integration of AM into local manufacturing. Many initiatives have been launched by institutions such as the National Industrial Development and Logistics Program and the Ministry of Industry and Mineral Resources. Activities include sponsoring and funding proof-of-concept projects, hosting industry-focused workshops, and retaining international consultants to provide insights on nationwide AM strategies.

Little nationally-funded AM research has occurred, except at the Technology Innovation Institute in Abu Dhabi, a government-funded research institution. Most research is small-scale and conducted by universities, with Khalifa University in Abu Dhabi being one of the most active. No conferences specifically focused on AM were held in 2022. However, AM system vendors were represented at several industrial trade shows, including the Dubai Air Show, ME RoTIC 2022, and ADIPEC 2022.

Egypt

by Khalid Abd Elghany

AM implementation is becoming more widespread in Egypt, especially in the medical sector. Four PBF systems are installed in Egypt, two metal systems from LASERTEC, a system from Concept Laser, and a Formiga P 110 polymer system from EOS. Many desktop 3D printers from a range of European and Chinese manufacturers are being used for dental applications and education.

Fig. 248. Spare part in an aluminum alloy and made using laser PBF, courtesy of CMRDI

Five local startup companies are producing small AM machines based on MEX and DLP processes. They are used primarily for dental products and the production of small spare parts. Several universities are in the process of developing their own 3D printers based on open-source MEX system designs available on the Internet.

Dentists, orthopedic surgeons, and craniofacial surgeons continue to be the largest users of AM in Egypt. In 2022, more than 1,300 custom stents for patients' missing teeth were made using AM. More than 50 custom surgical guides and templates were 3D printed for partial or total knee replacement surgeries. AM supported craniofacial surgeries by producing more than 60 surgical guides and an estimated seven Ti-6Al-4V implants.

The Egyptian government is working on a roadmap to support the implementation of AM in the industrial, medical, education, and cultural sectors. The government plans to allocate about €50 million from 2023 to 2025 toward purchasing new AM machines and local material production. The funds will support the installation of small 3D printers in high schools and public universities.

Israel

by Joseph Kowen

The AM industry in Israel continues to develop steadily. The AM innovation ecosystem is producing new processes and advances in existing technologies as industry adoption of AM expands.

Stratasys acquired Covestro's AM materials division and divested MakerBot by merging it with Ultimaker. MakerBot was originally acquired by Stratasys in 2013. Stratasys also made a $10 million investment in medtech startup Axial3D and acquired Riven, a developer of cloud-based quality assurance software. Nano Dimension announced in July 2022 that it had acquired 12% of Stratasys' shares in open market trading. It also entered the ceramic 3D printing market with the acquisition of Admatec Europe and Formatec in July 2022.

Massivit 3D's revenue grew by more than 40% compared to 2021. However, its share price on the Tel Aviv Stock Exchange fell by more than 50% in 2022. It launched the Massivit 10000 system for tooling applications and reported sales of five systems for 2022. 3DM announced it had signed a collaboration agreement for its laser printing engine to be tested on systems from EOS. XJet appointed a new CEO in April 2022. Several of the country's leading industrial companies, including Elbit Systems, Iscar, Israel Aerospace Industries, and Rafael, continue to develop applications for AM.

3D SIL is developing a novel system for printing medical-grade silicone materials. Polyfos is developing a multi-material VPP system. Noga 3D Innovations is working on photopolymers with improved performance for 3D printing applications. Assembrix has expanded its collaboration with Boeing and announced the integration of its production software with systems from SLM Solutions. Castor released an AM sustainability report based on AM part data collected on its cloud platform. Largix displayed its large-format machine for polypropylene and polyethylene at the K Düsseldorf 2022 show in Germany.

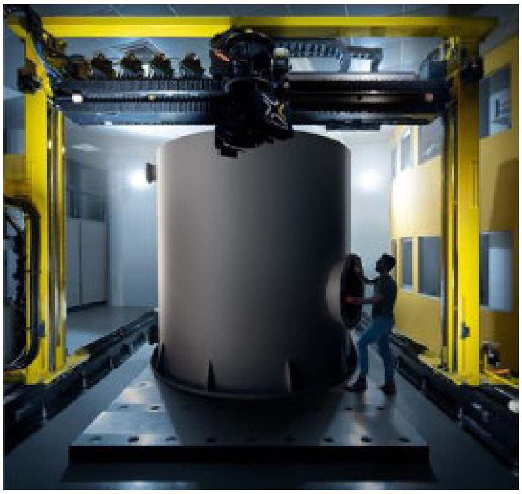


Fig. 249. Large-format printer, courtesy of Largix

The Israel Innovation Authority continues to fund new AM startups through its general startup support program. The Israel Institute of Materials and Manufacturing Technologies at the Technion offers research and testing services for AM applications. The 3D Printing Research and Development Center at Tel Aviv University commissioned an Optomec LENS system for research into metal AM applications.

New-Tech Events organized 3D-Day, a seminar on 3D printing, as part of the annual New-Tech Exhibition. The Technion Additive Manufacturing Center arranged daylong seminars in Haifa and Tel Aviv covering 3D printing topics for industry.

PART 6: RESEARCH AND DEVELOPMENT

Trends

by David Bourell

From 2020 through 2022, additive manufacturing (AM) research was influenced by the worldwide pandemic. By the start of 2023, research in most parts of the world had returned to normal. The AM research community continues to cover a broad range of topics reflecting the breadth of the field. Materials research continues to focus on polymers and metals. New software tools are being used for AM process modeling and other applications. Three broad trends are described briefly in the following paragraphs, along with examples.

Faster, better, less expensive. These motivators have been the focus of research from the beginning of AM, and they continue to be so today. Diverse examples include the development of digital twins (Edison Welding Institute) and new polymer materials such as thermosets (Savannah River National Lab). Modeling efforts are introducing a variety of novel approaches, such as hybrid curve fitting, artificial intelligence (AI) in design, Z-chunking, and K-means clustering. Metal AM simulation efforts tend to focus on laser powder bed fusion (PBF) and address every aspect of processing. For example, work at Penn State University is assessing the role of material composition on melt pool geometry.

Expanding capacity. A significant amount of research is aimed at the development of new and expanded AM capabilities. The approaches are diverse, including process development, sensing, and materials. Aerojet Rocketdyne is developing processes to increase the effective build height for PBF parts. Researchers at Ohio State University are studying metal lattice design to better understand and use these structures. Research at Paderborn University (Germany) focuses on assessing and increasing the shelf life of polyamide for laser PBF.

Increasing the application space. Research—particularly applied research—usually focuses on issues associated with specific applications. This category seeks to increase the number of possible processes, leading to new possibilities for AM applications. America Makes has funded several application-specific projects. Ursa Major Technologies is assessing AM for producing rocket parts. Blue Force Technologies is applying AM for other high-temperature applications. Boeing has an America Makes grant to develop the additive manufacture of hypersonic systems. Raytheon has a project to study the reflective optics of AM. The University of Dayton Research Institute is researching the additive manufacture of oil coolers.

Fig. 250. Rocket engine component made using AM, courtesy of Ursa Major Technologies

Patents

by Aidan Skoyles and Nicholas Eitsert

More than 8,000 U.S. patents were filed in the AM space in 2022, similar to filings in 2020 and 2021. These numbers are significantly higher than the volume of patents filed in prior years. The following graph and table show the growth of AM-related U.S. patents issued since 1998 (in gray). They also show the number of AM-related U.S. patent applications published since 2001 (in orange).

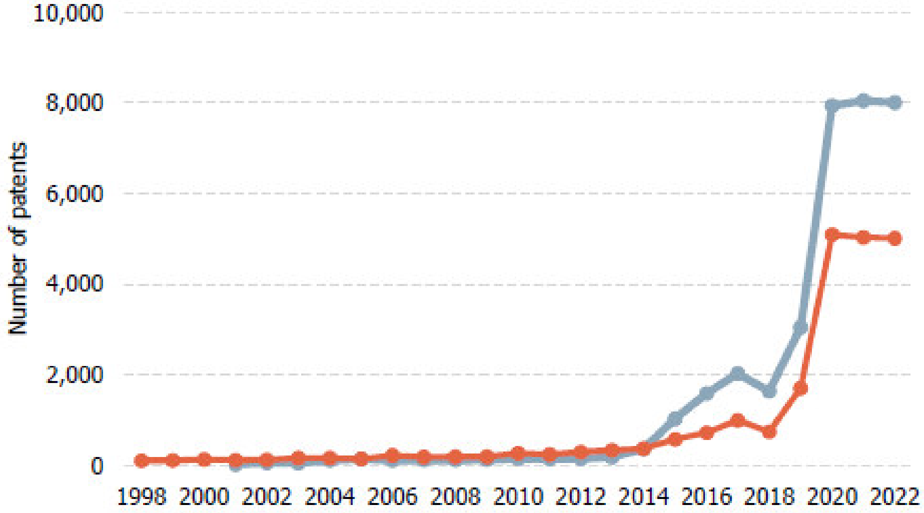


Fig. 251. Patent applications and patents issued by year; source: U.S. Patent and Trademark Office

In general, patent applications are not made public at the time of filing but are usually published 18 months after filing. Most patents and applications are for utility patents covering technical advancements. However, a small number are design patents, which protect the ornamental designs of products and hardware.

Year	Patents issued	Published applications
2022	5,010	8,009
2021	5,030	8,050
2020	5,092	7,944
2019	1,707	3,044
2018	745	1,636
2017	998	2,028
2016	722	1,589
2015	576	1,033
2014	368	361
2013	337	182
2012	294	148
2011	243	141
2010	265	148
2009	191	121
2008	193	113
2007	186	114
2006	216	111
2005	147	143
2004	162	112
2003	163	50
2002	125	54
2001	114	20
2000	132	
1999	109	
1998	105	

Source: U.S. Patent and Trademark Office

The jump in new AM patents (2020–2022) is at odds with the overall trend of a decline in patents issued following the pandemic. This may be due to an industry-wide caution on expanding investment in both R&D and patent protection at a time of economic uncertainty. Across all patents filed with the U.S. Patent Office, the number of granted U.S. patents dropped from about 350,000 in 2020 to about 327,000 in 2021, and then to about 323,000 in 2022.

The number of published applications has also held steady over the past two years. This likely signals a sustained but plateaued enthusiasm in AM-related patenting efforts across the industry. After robust growth in 2019, the continued high level of published patents is a sign of ongoing innovation and continued investment in AM.

Issued patents are categorized by sector, as shown in the following table. In general, the breakdown across sectors remained similar in 2022 compared to 2021. For the fourth consecutive year, AM hardware/methods had the highest proportion, accounting for about one-sixth of AM-related patents issued. This suggests core AM techniques remain an innovation focus despite growing AM adoption across an increasing range of industries. A slight increase in the proportion of automotive and medical/dental applications possibly reflects an effort to address supply chain issues in these industries. The diversity in subject matter of filed patents demonstrates continued innovation in AM across a broad range of industries.

	Patents issued (%)											
Sector	**'22**	**'21**	**'20**	**'19**	**'18**	**'17**	**'16**	**'15**	**'14**	**'13**	**'12**	**'11**
3D Printing - hardware and software	16	19	15	20	13	7	6	5	2	2	2	2
3D Printing – material	14	12	12	9	5	6	3	2	4	3	3	3
3D Printing – software	5	5	7	7	7	6	5	5	5	7	6	9
Academic institutions	4	4	4	3	2	3	2	3	3	3	3	3
Aerospace	5	5	6	12	12	13	12	11	14	15	14	10
Architectural	5	5	7	3	10	8	10	10	12	10	7	13
Consumer products/electronics	10	10	12	16	13	15	17	14	8	10	9	10
Government/military	3	3	5	1	2	1	0	1	1	0	1	1
Industrial/business machines	11	11	13	11	14	9	10	12	10	9	15	13
Medical/dental	7	6	5	9	12	16	17	22	24	24	19	19
Motor vehicles	9	8	5	4	6	8	12	11	12	12	13	12
Others	11	12	9	6	4	8	7	5	6	4	8	5

Source: U.S. Patent and Trademark Office

The following table shows the distribution of entities obtaining patents from 2011 to 2022. The numbers remained consistent during the period. Companies continue to obtain far more patents than all individuals, non-profit organizations, and universities combined. U.S. patents are issued in the name of the inventor(s) but are usually assigned to the company employing them.

	Patents issued (%)											
Entity	**'22**	**'21**	**'20**	**'19**	**'18**	**'17**	**'16**	**'15**	**'14**	**'13**	**'12**	**'11**
Company	83	85	84	85	83	86	88	89	88	86	91	90
Individual	7	6	6	6	8	7	6	5	4	6	2	2
Lab/non-profit organization	3	2	3	2	4	2	1	1	1	1	0	0
University	7	7	7	7	6	5	5	6	7	6	6	7

Source: U.S. Patent and Trademark Office

Companies with the greatest number of AM-related published patent applications in 2022 are listed in the following table.

Company	Published patent applications
HP	214
GE	30
Seiko Epson	28
Desktop Metal	23
Carbon	20

Source: U.S. Patent and Trademark Office

The accuracy of the data is limited by subjective decisions (i.e., what to include or exclude) in the search process. Efforts were made to remove false positives, such as products made by additive processes that are not typically viewed as AM technologies.

Patent litigation

Some patents have been the subject of patent infringement litigation in federal courts. As in previous years, litigation in the AM space remains relatively sparse with some notable exceptions.

A dispute between Markforged and Continuous Composites is ongoing. In 2021, Continuous Composites sued Markforged, claiming infringement of four patents related to continuous fiber 3D printing. Specifically, it was alleged that Markforged's Continuous Fiber Reinforcement process infringed patents held by Continuous Composites. Markforged responded with a motion to dismiss various pre-suit damages.

Throughout 2022, Markforged filed seven petitions for inter partes review at the U.S. Patent and Trademark Office, challenging the validity of the asserted patents. The Patent Office instituted one petition in October 2022, finding that Markforged demonstrated a reasonable likelihood of prevailing on at least one challenged claim. An additional three petitions were denied institution, and three more petitions are currently pending before the Patent Office (as of early 2023) and the case is proceeding. A jury trial in Delaware is set for December 2023.

The first major patent dispute in 3D bioprinting has concluded. In June 2021, Swedish bioprinting company Cellink filed a preemptive suit against Organovo in Delaware District Court. Cellink asked the court to declare it was not infringing eight Organovo patents related to the 3D printing of viable cells and tissues. Organovo responded by asserting claims of patent infringement against Cellink, naming the Bio X bioprinter as an allegedly infringing product. Cellink then challenged the validity of several Organovo bioprinting patents before the U.S. Patent and Trademark Office's Patent Trial and Appeal Board.

Organovo and Cellink (now BICO) settled their dispute in February 2022. Organovo agreed to license the accused patents to BICO in exchange for BICO's dismissal of legal proceedings against Organovo. The settlement included a $1.5 million upfront payment to Organovo and a 1.5% to 8.0% royalty on BICO's net sales.

The University of Tennessee and Battelle Institute attracted controversy after they were issued a U.S. patent titled "Cable-driven additive manufacturing system." The patent was funded by the Department of Energy under Oak Ridge National Laboratory's Sky Big Area Additive Manufacturing ("SkyBAAM") program. The patent was scrutinized by open-source advocates as allegedly copying an earlier open-source technology known as Hangprinter. As of January 2023, a GoFundMe fundraiser promising to challenge the validity of the disputed patent has raised about $20,000, with a target of $60,000. The dispute is ongoing.

Consortia and collaboration

Non-competitive collaboration has played an important role in the development of the AM industry. Among the types of collaborations are industry roadmapping, consortia, user groups, and online forums. Collaborations also occur among educational entities and working groups dedicated to advancing AM industry standards, curricula, and training materials.

Seminars, workshops, conferences, and exhibitions have provided an opportunity for the dissemination of best practices and new applications. They often include the display of AM parts and equipment. Workshops and roadmapping events on AM help guide industry, academic, and government organizations. These events bring together leaders to create a shared vision of the future.

ASTM AM Center of Excellence

by Mohsen Seifi

The AM industry has seen tremendous growth and development over the past few decades. As a key organization, ASTM International is driving advancement and adoption of AM. ASTM created the ASTM F42 Committee in 2009 to bring together AM experts from around the world to contribute to the development of relevant industry standards. Since its inception, ASTM F42 has grown to include over 1,200 members from more than 35 countries.

In 2011, ASTM and ISO signed a Partnership Standard Development Organization (PSDO) Agreement to jointly develop internationally recognized standards in AM. As of March 2023, a total of 47 standards have been published, and 87 more are in development. One of the barriers to expediting the standards development process is a lack of reliable information and data to substantiate the requirements set in the standards.

To address this challenge, ASTM launched the Additive Manufacturing Center of Excellence (AM CoE) in 2018 in partnership with several top organizations. The center's mission is to accelerate the development and adoption of robust, game-changing technologies by supporting standardization, developing training and certification programs. Also, it is providing market intelligence, business strategy, and advisory services through Wohlers Associates.

Now in its fifth year of operation, the AM CoE has made significant contributions to the advancement of AM. By bridging the gap between standards development and research and development, the center has conducted cutting-edge research in collaboration with its partners. This work has impacted existing standards and those currently under development. The AM CoE has developed several training programs to ensure the AM workforce has the knowledge and skills it needs to stay current. Furthermore, the center has developed certification programs for additive manufacturers and personnel to demonstrate their compliance with international standards.

America Makes

by John Wilczynski

America Makes, founded in 2012, is the flagship institute for Manufacturing USA. It is the leading public-private partnership for AM technology and education in the U.S. Its mission is to accelerate the U.S. adoption of AM and enhance manufacturing competitiveness by focusing on AM technology, education and workforce development, and AM ecosystems.

Headquartered in Youngstown, Ohio, America Makes has nearly 240 members from academia, government, industry, and economic development organizations. The institute has sponsored more than 250 projects since its inception. They include projects on materials and processes, integrated value chains, and workforce reskilling and upskilling.

In 2022, members actively engaged in 77 projects totaling over $43 million in public and private funding. America Makes follows a member-driven technology roadmap, with applied research projects covering a wide range of subjects. The institute works through inter-organizational teams that are highly collaborative and draw on the strengths of each participating member.

Education and workforce development remains a central pillar for America Makes. It supports pre-competitive innovation by organizing education and training programs to grow and strengthen the AM workforce. America Makes engaged with more than 8,300 individuals in 2022. It continues to collaborate with regional, state, and national partners to ensure AM is a priority and growing in both reach and impact.

Since January 2021, the institute has been instrumental in nearly 70 engagements that cover trends, gaps, and interests in AM technology maturation. Within these engagements, individuals from industry, government, academia, national labs, and non-profit organizations share their perspectives. They serve to refine the strategic direction of America Makes and the wider AM community.

The institute is connected to a large national network that provides members with access to a range of AM capabilities and expertise. It has satellite locations at the University of Texas at El Paso, Texas A&M Engineering Experiment Station, and the National Institute for Aviation Research at Wichita State University.

Fraunhofer

by Bernhard Müller

Germany's Fraunhofer-Gesellschaft, which translates to "Fraunhofer Society," is one of the world's leading applied research organizations. It develops key technologies and facilitates commercial technology transfer. Founded in 1949, Fraunhofer currently operates 76 institutes and research organizations. Most of the organization's 30,000 employees are scientists and engineers. Its annual research budget is €2.9 billion, €2.5 billion of which is generated through contract research.

AM is a major field of research within Fraunhofer, covering production, materials, life sciences, innovation, defense and information, and communication technologies. The Fraunhofer Competence Field Additive Manufacturing ("Fraunhofer Additive") bundles all Fraunhofer AM activities from 18 member institutes under one roof. It serves as a central point of contact to Fraunhofer customers and partners. AM research areas of Fraunhofer Additive are engineering, materials, technologies, quality, and software.

In 2022, Fraunhofer presented a novel interactive booth concept at Rapid.Tech 3D in May (Erfurt, Germany) and Formnext in November (Frankfurt, Germany). The same year, Fraunhofer presented a five-part webinar series launched as a prelude to its bi-annual AM event, the Fraunhofer Direct Digital Manufacturing Conference. It was scheduled for March 2023 in Berlin, Germany.

One highlight from Fraunhofer AM research in 2022 is FingerKIt, a process for creating AI-generated, individualized, 3D-printed finger-joint implants. A consortium of five Fraunhofer institutes, including IAPT, IKTS and IWM, are using binder jetting (BJT) with titanium powder for a high level of detail and good surface quality.

Fig. 252. FingerKIt implant, courtesy of Fraunhofer

Also in 2022, Fraunhofer IWM developed 3D-printed Triple Periodic Minimal Surfaces—structures that are said to show extraordinary energy absorption properties. They can be numerically modeled based on IWM's own surrogated models for design to purpose.

The Fraunhofer Cluster of Excellence CPM brings together many Fraunhofer institutes to develop "Programmable Materials," which perform system functions through their internal design. Their inner structure is designed to control and reversibly change material properties and behavior, including locally varying functions. Fraunhofer CPM believes AM is a key enabling technology to manufacture fully functional programmable materials via processing smart materials such as shape-memory polymers and alloys. The goal is to combine them with the exceptional freedom of design that AM offers.

In 2022, the first technical applications were explored for 3D-printed programmable materials. ProgMatCon, the International Conference on Programmable Materials, took place as a hybrid event in July 2022 in Berlin at the Fraunhofer-Forum. The Fraunhofer team and invited researchers from Caltech, AMOLF Amsterdam, University College London, and Leibniz INM shared research results to encourage a shift in materials research.

The German KISS consortium, with 11 members from industry and research, including Fraunhofer IWU, is pursuing a new approach. The aim is to match AM technology with market demands for a sustainable AM economy. An AI-driven semantic matching platform will be established with SEMPER-KI. It is focusing on critical and crisis-driven demands from the healthcare and social sector. The KISS project is funded by the German Federal Ministry for Economic Affairs and Climate Action.

Women in 3D Printing

by Nora Touré and Kristin Mulherin

Women in 3D Printing (Wi3DP) is a non-profit organization originally dedicated to promoting, supporting, and inspiring women involved with AM. It has recently broadened its mission to supporting an industry that is more representative of the world in which it operates. It was formed in 2014 by Nora Touré and has since become a global community of more than 30,000 people. It has over 100 local chapters in 36 countries.

Fig. 253. Worldwide distribution of Wi3DP chapters, courtesy of Wi3DP

Women and other underrepresented groups have a disproportionately low presence in product development, engineering, and manufacturing worldwide. Wi3DP seeks to close this gap in AM. The organization supports the work of leaders, engineers, business professionals, teachers, researchers, artists, designers, and others who are underrepresented.

The volunteer-run organization is dedicated to developing resources aimed at creating a stronger AM workforce and industry. The Wi3DP local chapters organize networking events, panel sessions, and on-site tours. These events are mainly organized and led by local ambassadors, area managers, and regional chairs, with most chapters meeting on a quarterly basis.

The organization's resources include a database of women speakers, a job board, and industry surveys and reports. The annual Technology, Industry, People, and Economics (TIPE) conference, held each January, features more than 150 women speakers from around the world. It spans three days, with two career fairs on the third day—one for each hemisphere. The TIPE event has been designed as a human-centric event that expands beyond technology.

In 2021, Wi3DP formally introduced diversity, equity, and inclusion programming. The initiative offers insight into the AM landscape with resources aimed at improving the industry. The Wi3DP NextGen Program is a strategic initiative focused on inspiring the next generation of AM professionals. The program provides mentorships to students and recent graduates, and hosts networking opportunities for students to connect with AM industry professionals.

In May 2022, a partnership was announced between Wi3DP and SME, a non-profit professional association for educating and advancing people in manufacturing. The collaboration has initially included four initiatives: 1) co-production of the TIPE conference, 2) a "Wi3DP Showcase" at SME's RAPID + TCT 2023 event in Chicago, 3) an expansion of the NextGen Program in cooperation with SME, and 4) co-authorship of the Diversity for Additive Manufacturing Annual Report.

Mobility Goes Additive

by Stefanie Brickwede

The Mobility Goes Additive (MGA) network is an industry consortium dedicated to bridging the gap between the needs of users and solutions from suppliers. As part of MGA, about 150 members from across the AM value chain address issues in mobility, aerospace, railway, automotive, and healthcare. The network also discusses general AM topics that include sustainability and energy efficiency.

MGA members share their experiences with AM materials and processes. They participate jointly in working groups and focus groups to overcome challenges and solve problems that a company working alone might not achieve.

Shared topics include standardization, materials, and applications from a wide range of industries. WeBoostAM.com is an open-access online platform offering information on applications, standards, materials, and training concepts. MGA has also created the Industrial Additive Manufacturing Hub at the network's headquarters in Berlin. It provides a meeting place, co-working space, and training facility for members. It houses an extensive exhibition that highlights AM applications.

Another goal of the network is to raise awareness of AM. MGA organizes events such as an annual student competition and a Women in AM conference. It also co-hosts Techjourney visits to AM-relevant regions, hoping to improve cooperation between countries. MGA serves as a resource for providing input to organizations, including the European Commission and political decision makers.

Partnerships

Many AM-related partnerships have formed among organizations worldwide. They involve service providers, systems manufacturers, producers of materials and software, research groups, and a broad range of AM users. Partnerships are becoming more common in areas where a single company cannot meet the expanding needs of one or more markets.

The following table includes notable partnerships and collaborations by date, organization, and area of focus. It provides a sampling of partnerships in AM from March 2022 through March 2023.

Organizations	Main focus
March 2022	
3D Systems, Dussur	Expand AM use in Middle East
3D Systems, Enhatch	Workflow for patient-specific medical devices
Curify Labs, Natural Machines	Platform for AM medication
Sandvik Mining and Rock Solutions, Boliden	3D printing of metal spare parts
Sennheiser, Heraeus Amloy Technologies	Producing metal AM earphones
April 2022	
DOD Defense Innovation Unit, ICON	Construction of 3D-printed barracks
Foxconn, Triditive	New metal BJT system
Odette Lunettes, Materialise	3D-printed frames for eyeglasses
Stratasys, Lockheed Martin	Qualification of Antero 840CN03 material
May 2022	
Conflux Technology, GKN Additive	New heat exchanger designs for AM production
EOS and Hyperganic	Design and production service for large space parts
GE Additive, U.S. Air Force	Replacement metal AM parts for military equipment
June 2022	
Ingersoll, Meld, U.S. Army	Vehicle-sized metal AM system

Organizations	Main focus
Lufthansa Technik, Premium AEROTEC	Flight certification of load-bearing metal AM part
July 2022	
Eli Lilly, Triastek	3D-printed medicines
Hasbro, Formlabs	Custom action figures
Lawrence Livermore National Laboratory, Ampcera	3D-printed parts for lithium-ion batteries
MeaTech, Umami	3D-printed seafood
Precise Bio, Carl Zeiss Meditec	3D-printed implants
Replique, Alstom	End-use AM parts for transportation sector
August 2022	
Aston Martin, Divergent Technologies	3D-printed aluminum sub-frame
Johnson & Johnson, T&R Biofab	3D bioprinting of implants
Lincoln Electric Additive Solutions, Baker Industries, General Atomics Aeronautical Systems	AM-produced steel tools for composites manufacturing
September 2022	
Evonik, Stratasys	New photopolymer material for vat photopolymerization (VPP) system
IperionX, Panerai	3D-printed watch cases made from recycled titanium
Royal Netherlands Navy, Nanoe	3D printing of parts at sea
Sakuú, NGK	Ceramic materials for 3D-printed batteries
October 2022	
Citroën, BASF	Lightweight AM car parts with lattice structures
Swiss Federal Institute of Technology Lausanne, CSEM	R&D center for 3D microfabrication
November 2022	
3D Systems, Wematter	Worldwide distribution of low-cost PBF system
6K Additive, Fraunhofer ILT	Lifecycle assessment of laser PBF
AddUp, Dassault Aviation	Industrialization of metal AM
EOS, PostProcess Technologies	Powder processing optimization software
Sakuú, LiCAP	Electrodes for AM-produced batteries
Waseda University, University of Pittsburgh	Reducing distortion in metal AM parts
December 2022	
Amaero, Rabdan	Production of metal AM parts and powders
Sintavia, Lockheed Martin	Metal AM solutions for aerospace parts
January 2023	
AddUp, MT Aerospace	DED solutions for aerospace applications
BEAMIT Group, Leonardo	AM parts for aerospace applications
ConocoPhillips, Equinor, Shell, TotalEnergies and Vår Energi	Spare parts produced using AM
February 2023	
Thales, SWISSto12	AM parts for satellites

Source: Wohlers Associates

Other groups and associations

In many countries, AM professionals have come together to create groups and associations. The goal of most of them is to promote the development and adoption of AM.

Association name	Country	Website
Additive Manufacturing Association of India	India	www.amsi.org.in
Additive Manufacturing Austria	Austria	www.am-austria.com
Additive Manufacturing Green Trade Association	U.S.	www.amgta.org
Additive Manufacturing UK	UK	www.am-uk.org.uk
Additive & 3D Manufacturing Technologies Association of Spain	Spain	www.addimat.es
Alberta Additive Manufacturing Network	Canada	www.albertaamn.com
AM Technical Community	U.S.	www.sme.org/engage/communities/additive-manufacturing-community
AM4GR	Greece	www.am4gr.com
AMable	Europe	www.amable.eu
Association for Metal Additive Manufacturing	U.S.	www.my.mpif.org/MPIF/Associations/AMAM
Associazione Italiana Tecnologie Additive	Italy	www.aita3d.it
Canada Makes	Canada	www.canadamakes.ca
Collaborative Programme in Additive Manufacturing (CPAM)	South Africa	www.cpam.technology
Dansk AM Hub	Denmark	www.am-hub.dk/en
Finnish Additive Manufacturing Ecosystem	Finland	www.fame3d.fi/about
France Additive	France	www.franceadditive.tech
Hong Kong 3D Printing Association	Hong Kong	www.hk3dpa.org/en
Japan 3D Printing Industrial Technology Association	Japan	www.3dprint.or.jp
National Additive Manufacturing Association	U.S.	www.additivemfg.org
Rapid Product Development Association of South Africa	South Africa	www.site.rapdasa.org
RApid Prototyping and Innovative MAnufacturing Network	Slovenia	www.rapiman.net
Shanghai Additive Manufacturing Association	China	www.samafb.org
Swiss Additive Manufacturing Group	Switzerland	www.swissmem.ch/en/products-services/networking/specialist-groups/swiss-additive-manufacturing-group
Taiwan Aerospace Additive Manufacturing Industry Association	Taiwan	www.taamia.org.tw
Technology Research Association for Future Additive Manufacturing	Japan	www.trafam.or.jp
Turkish Additive Manufacturing Association	Turkey	www.additiveturkey.org

Source: Wohlers Associates

Corporations, government agencies, universities, and others have established AM centers of excellence. As with professional associations, the aim is to promote the development and adoption of AM. Some centers focus on developing a segment of AM. Many of the centers of excellence from around the world are listed in the following table.

Center of excellence	Lead	Country	Website
3D Printing and Digital Manufacturing Center of Excellence	HP	Spain	www.hp.com
Additive Manufacturing Center of Excellence	ASTM International	U.S.	www.amcoe.org
Additive Manufacturing Hub	Australian Manufacturing Technology Institute Limited	Australia	www.amhub.net.au
Advanced Additive Manufacturing Center	3D Systems	Italy	www.3dsystems.com
Advanced Manufacturing Center	Department of Science and Technology	Philippines	www.amcen.dost.gov.ph
Advance Manufacturing Transformation Centre	Siemens	Singapore	www.new.siemens.com/sg/en/products/services/industry/amtc.html
Center of Additive Manufacturing Excellence	Boeing	U.S.	www.boeing.com
Center of Excellence	Arkema	France	www.arkema.com
Centre for Additive Layer Manufacturing	University of Exeter	UK	www.emps.exeter.ac.uk/engineering/research/etg/centres/calm
Centre for Additive Manufacturing	University of Nottingham	UK	www.nottingham.ac.uk/research/groups/cfam
National Additive Manufacturing Innovation Cluster Singapore	Nanyang Technological University	Singapore	www.namic.sg
National Center for Additive Manufacturing	Union Ministry of Electronics and Information Technology	India	www.meity.gov.in
National Center for Additive Manufacturing Excellence	Auburn University	U.S.	www.eng.auburn.edu/research/centers/additive/index
National Centre for Additive Manufacturing	Manufacturing Technology Centre	UK	www.ncam.the-mtc.org
Safran Additive Manufacturing Campus	Safran Group	France	www.safran-group.com
TechCenter Additive Manufacturing	Thyssenkrupp	Germany	www.thyssenkrupp.com/en/stories/techcenter-additive-manufacturing--new-opportunities-for-industries
TWI Innovation Centre for Additive Manufacturing	TWI	UK	www.twi-global.com/innovation-network/innovation-centres/additive-manufacturing-ic
W.M. Keck Center for 3D Innovation	University of Texas at El Paso	U.S.	www.keck.utep.edu

Source: Wohlers Associates

AM standards

Several national and international SDOs are addressing the development of AM standards. ASTM International and the International Standards Organization (ISO) have accomplished the most to date.

SDOs in the U.S. that create AM standards include the American Society of Mechanical Engineers (ASME), American Welding Society (AWS), and Underwriter Laboratories (UL). Globally, they include the Association of German Engineers (VDI), British Standards Institution (BSI), German Institute for Standardization (DIN), Norwegian truth (DNV), and SAE International. The Additive Manufacturing Standardization Collaborative, discussed in an upcoming section, aims to coordinate standards development across participating SDOs.

ASTM Committee F42

by John Slotwinski and Pat Picariello

ASTM formed International Committee F42 on Additive Manufacturing Technologies in 2009. Its goal is to develop consensus standards on AM across multiple industrial sectors. As of January 2023, the committee consisted of more than 1,150 individual members in 39 countries. About 35% of the members are located outside the U.S. The right to vote on proposed standards requires membership in F42, but participation in meetings and discussions does not.

The range of F42 technical subcommittees continues to expand. Technical subcommittees include Test Methods (F42.01), Design (F42.04), Materials and Processes (F42.05), Environmental Health and Safety (F42.06), Applications (F42.07), Data (F42.08), and Terminology (F42.91). The final subcommittee is the U.S. Technical Advisory Group (TAG) to the International Organization for Standardization Technical Committee (ISO/TC) 261 on Additive Manufacturing (F42.95). TAG develops the official U.S. response to any standards up for vote within ISO/TC 261. This coordination helps the two organizations ensure compatible and complementary standards activities.

As of January 2023, ASTM International had published 43 AM industry standards. The following table provides published standards on AM from ASTM International and a partnership between ASTM and ISO.

Standard	Title
F2924-14	Standard specification for additive manufacturing titanium-6 aluminum-4 vanadium with powder bed fusion
F2971-13	Standard practice for reporting data for test specimens prepared by additive manufacturing
F3001-14	Standard specification for additive manufacturing titanium-6 aluminum-4 vanadium ELI (extra low interstitial) with powder bed fusion
F3049-14	Standard guide for characterizing properties of metal powders used for additive manufacturing processes

Standard	Title
F3055-14a	Standard specification for additive manufacturing nickel alloy (UNS N07718) with powder bed fusion
F3056-14	Standard specification for additive manufacturing nickel alloy (UNS N06625) with powder bed fusion
F3091/F3091M-14	Standard specification for powder bed fusion of plastic materials
F3122-14	Standard guide for evaluating mechanical properties of metal materials made via additive manufacturing processes
F3184-16	Standard specification for additive manufacturing stainless steel alloy (UNS S31603) with powder bed fusion
F3187-16	Standard guide for directed energy deposition of metals
F3213-17	Standard for additive manufacturing—Finished part properties—Standard specification for cobalt-28 chromium-6 molybdenum via powder bed fusion
F3301-18a	Standard for additive manufacturing—Post processing methods—Standard specification for thermal post-processing metal parts made via powder bed fusion
F3302-18	Standard for additive manufacturing—Finished part properties—Standard specification for titanium alloys via powder bed fusion
F3318-18	Standard for additive manufacturing—Finished part properties—Specification for AlSi10Mg with powder bed fusion—Laser beam
F3413-19e1	Guide for additive manufacturing—Design—Directed energy deposition
F3490-21	Practice for additive manufacturing—General principles—Overview of data pedigree
F3500-21	Additive manufacturing of metals—Qualification principles—Part 1: General qualification of machine operators
F3529-21	Additive Manufacturing—General Principles—Guide for design for material extrusion processes
F3456-22	Standard guide for powder reuse schema in powder bed fusion processes for medical applications for additive manufacturing feedstock materials
F3466-22	Additive manufacturing of metals—Qualification principles—Part 2: Qualification of operators for powder bed fusion—Laser beam
F3467-22	Additive manufacturing of metals—Qualification principles—Part 3: Qualification of operators for powder bed fusion—Electron beam
F3468-21	Additive manufacturing of metals—Qualification principles—Part 4: Qualification of operators for directed energy deposition—Laser beam
F3477-22	Additive Manufacturing—Qualification principles—Laser-based powder bed fusion of polymers—Part 1: General principles, preparations of test specimens
F3488-22	Standard guide for additive manufacturing design—Decision guide
F3522-22	Standard guide for Additive Manufacturing of Metals—Feedstock Materials—Guide for Assessment of Powder Spreadability
F3530-22	Standard guide for additive manufacturing—Design—Post-processing for metal PBF-LB
F3546-22	Standard guide for additive manufacturing—Environment, health and safety—Standard guideline for use of metallic materials
F3554-22	Specification for additive manufacturing—Finished part properties—Nickel alloy (UNS G43400) via PBF-LB for Transportation Applications
F3560-22	Specification for additive manufacturing data common exchange format for particle size analysis by light scattering
F3567-22	Standard guide for additive manufacturing—Design—Part 3: Electron beam powder bed fusion of metals
F3571-22	Standard guide for additive manufacturing—feedstock—Particle shape image analysis by optical photography to identify and quantify the agglomerates/satellites in metal powder feedstock

Standard	Title
F3572-22	Practice for additive manufacturing—General principles—Part classifications for additive manufactured parts used in aviation
F3606-22	Standard guide for additive manufacturing—Feedstock materials—Testing moisture content in powder feedstock
F3607-22	Specification for additive manufacturing—Finished part properties—Standard specification for maraging steel via powder bed fusion
ISO/ASTM52901-16	Standard guide for additive manufacturing—General principles—Requirements for purchased AM parts
ISO/ASTM52910-18	Additive manufacturing—Design—Requirements, guidelines and recommendations
ISO/ASTM52911-1-19	Additive manufacturing—Design—Part 1: Laser-based powder bed fusion of metals
ISO/ASTM52911-2-19	Additive manufacturing—Design—Part 2: Laser-based powder bed fusion of polymers
ISO/ASTM52902-19	Additive manufacturing—Test artifacts—Geometric capability assessment of additive manufacturing systems
ISO/ASTM52907-19	Additive manufacturing—Feedstock materials—Methods to characterize metallic powders
ISO/ASTM52904-19	Additive manufacturing—Process characteristics and performance—Practice for metal powder bed fusion process to meet critical applications
ISO/ASTM52921-13 (2019)	Standard terminology for additive manufacturing—Coordinate systems and test methodologies
ISO/ASTM52903-1-20	Additive manufacturing—Material extrusion-based additive manufacturing of plastic materials—Part 1: Feedstock materials
ISO/ASTM52903-2-20	Additive manufacturing—Material extrusion-based additive manufacturing of plastic materials—Part 2: Process equipment
ISO/ASTM52915-20	Specification for additive manufacturing file format (AMF) version 1.2
ISO/ASTM52942-20	Additive manufacturing—Qualification principles—Qualifying machine operators of laser metal powder bed fusion machines and equipment used in aerospace applications
ISO/ASTM52941-20	Additive manufacturing—System performance and reliability—Acceptance tests for laser metal powder bed fusion machines for metallic materials for aerospace application
ISO/ASTM52930-21	Additive manufacturing—Qualification principles—Installation, operation and performance (IQ/OQ/PQ) of PBF-LB equipment
ISO/ASTM52950-21	Additive manufacturing—General principles—Overview of data processing
ISO/ASTM52900-21	Additive manufacturing—General principles—Fundamentals and vocabulary (Process terms and definitions from this standard have been fully adopted in the *Wohlers Report*.)
ISO/ASTM52909-22	Additive manufacturing of metals—Finished part properties—Orientation and location dependence of mechanical properties for metal powder bed fusion
ISO/ASTM52925-22	Additive manufacturing of polymers—Feedstock materials—Qualification of materials for laser-based powder bed fusion of parts

Source: ASTM International

As of January 2023, more than 70 work items were under development. They are the first steps toward drafting new standards or revising existing ones. Among them are a guide for measuring and characterizing the surface texture for metal PBF parts and specifications for AM personnel qualification. The work also includes guidelines for authenticating and protecting intellectual property, feedstock specifications, and a guide on designing for vat photopolymerization (VPP).

In close collaboration with ISO/TC 261, more than 40 additional work items are under development.

The F42 committee met in a hybrid mode at the Colorado School of Mines in March 2022 and in-person in Augsburg, Germany in September 2022. The planned annual meetings for 2023 are at Pennsylvania State University (March 2023) and South Korea (September 2023). All meetings are held jointly with ISO/TC 261.

ISO/TC 261

by Christian Seidel

ISO Technical Committee 261 on Additive Manufacturing (ISO/TC 261) was established in 2011. The committee has a unique partnership with the ASTM Committee F42 on Additive Manufacturing Technologies. The ISO/TC 261 committee includes seven approved working groups (WG) and joint working groups (JWG).

ISO/TC 261	Title or Working Group	Example projects
WG 1	Terminology	ISO/ASTM 52900-21 Additive manufacturing—General principles—Fundamentals and vocabulary
WG 2	Processes, systems, and materials	ISO/ASTM TS 52930:2021 Additive manufacturing—Qualification principles—Installation, operation, and performance (IQ/OQ/PQ) of laser PBF equipment
WG 3	Test methods and quality specifications	ISO/ASTM 52902:2019 Additive manufacturing—Test artifacts—Geometric capability assessment of additive manufacturing systems
WG 4	Data and design	ISO/ASTM CD TR 52918 Additive manufacturing—Data formats—File format support, ecosystem, and evolutions
WG 6	Environment, health, and safety	ISO/ASTM 52931:2023 Additive manufacturing of metals—Environment, health, and safety—General principles for use of metallic materials
JWG 10	Additive manufacturing in aerospace applications – joint with ISO/TC 44/SC 14	ISO/ASTM 52941:2020 Additive manufacturing—System performance and reliability—Acceptance tests for laser PBF machines for metallic materials for aerospace application
JWG 11	Additive manufacturing for plastics – joint with ISO/TC 61/SC 9	ISO/ASTM 52936-1:2023 Additive manufacturing of polymers—Qualification principles—Part 1: General principles and preparation of test specimens for laser PBF

Source: ISO/TC 261

In September 2022, the committee met in person after a prolonged period of having online meetings. Over 200 delegates gathered in Augsburg, Germany for a week-long series of meetings.

Fig. 254. Attendees at the plenary meeting of the ISO/TC 261 committee in Augsburg, Germany, courtesy of Christian Seidel

Improvements in the standards development process adopted in 2021 have guided ISO/ASTM cooperation. To ensure that industry needs are best identified and addressed by ISO/TC 261, two industry experts were added to the management team. Fabio Sant'Ana of Brazil and Chaw-Sing Ho of Singapore are focusing on business development. The first project idea to improve standards for the oil and gas industry was discussed and approved at the September 2022 meeting.

After four years in the group and 11 years working in international standards development, Christian Seidel resigned as ISO/TC 261 committee chair. The March 2023 committee meeting at Penn State University in the U.S. was his final meeting as committee chair.

AM Standardization Collaborative

by Kevin Jurrens

America Makes and the American National Standards Institute (ANSI) established the Additive Manufacturing Standardization Collaborative (AMSC) in 2016. Its aim is to coordinate and accelerate the development of industry-wide AM standards and specifications consistent with the needs of the AM community.

The AMSC was launched following two planning meetings involving a broad cross section of AM stakeholders. It seeks to address increased coordination and communication challenges caused by a growing number of SDOs writing AM standards. The AMSC supports the continued growth of the AM industry by reaching consensus on the needs and priorities of standards. It also identifies gaps in existing activities and encourages SDOs to develop standards.

In June 2018, the AMSC issued a second version of its Standardization Roadmap for Additive Manufacturing. It was developed with contributions from hundreds of subject matter experts from industry, government, and academia. The roadmap identifies SDOs involved in AM and lists published standards and activities in progress. It also identifies gaps that, if filled, will help grow the AM industry.

The first version of the standardization roadmap was released in February 2017 and identified 88 gaps in standards. The second version identified 93 gaps. Of the identified gaps, 18 were categorized as high priority, 51 as medium priority, and 24 as low priority. R&D is needed for 65 of the identified gaps before standards development can proceed on these topics.

The AMSC continues to engage with SDOs, industry sectors, and AM experts to track progress against standards gaps and to refine the roadmap. In September 2022, the AMSC launched development of Version 3 of the Standardization Roadmap. This update will ensure that the roadmap remains relevant and aligns with current needs and priorities. Contributions from subject matter experts will again be used to update the standards gaps, priorities, and progress since the previous version. The new version is expected to be released in June 2023. Further details on AMSC activities can be found at www.ansi.org/standards-coordination/collaboratives-activities/additive-manufacturing-collaborative.

AM activities at NASA

by John Vickers

NASA's AM focus emphasizes investments in revolutionary technologies and sharing knowledge about innovations for missions in science, exploration, aeronautics, and technology. AM activities and commercial partnerships are growing considerably across all 10 NASA field centers and span dozens of research, education, and operational projects.

NASA has released a call for a Space Technology Research Institute (STRI) focused on accelerating AM certification with model-based engineering tools. The goal of the STRI is to strengthen ties to U.S. universities through long-term, sustained investment in critical AM research and technology development.

NASA has continued advancement of AM for rocket propulsion applications under the Rapid Analysis and Manufacturing Propulsion Technology project. The initiative addresses large-scale AM, novel alloy advancement, and multi-metal AM. The project has completed hot-fire testing of channel-wall-cooled thrust chambers made using laser PBF and bimetallic nozzles made using directed energy deposition (DED). The GRCop-42 alloy has been commercialized for use in laser PBF. NASA has worked with several commercial space companies planning to use this material for flight applications.

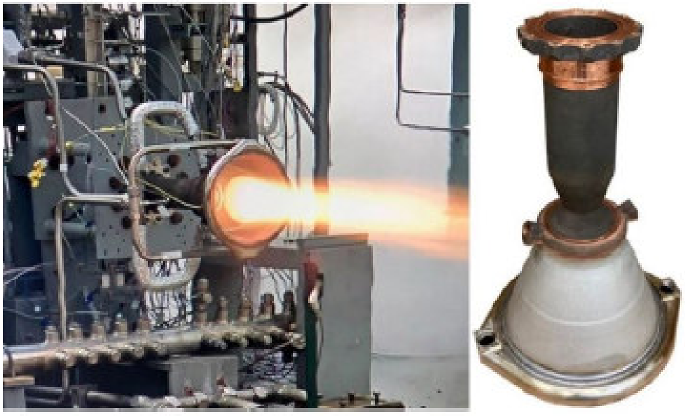


Fig. 255. Rocket engine test of a multi-metal thrust chamber, courtesy of NASA

NASA's In-Space Manufacturing project is focused on demonstrating AM in the microgravity of space and reduced gravity lunar environments. The project is developing AM technologies to print electronics, sensors, and multi-material products. Research is also being performed to recycle feedstock materials and to outfit a deep space/lunar habitat using multiple AM technologies.

The In Space Production Applications program selected many proposals in 2022 to encourage the use of in-space AM in the International Space Station. The goal is to create advanced materials and products to make commercial manufacturing a reality in space.

The Moon-to-Mars Planetary Autonomous Construction Technology project is focused on developing technologies to demonstrate the 3D printing of infrastructure on the moon. Landing pads, shelters, habitats, roadways, and blast shields are all under consideration, as shown in the following envisioned lunar construction site image. NASA has awarded ICON, a construction technology company, a $57 million Small Business Innovation Research project to develop lunar construction processes and equipment.

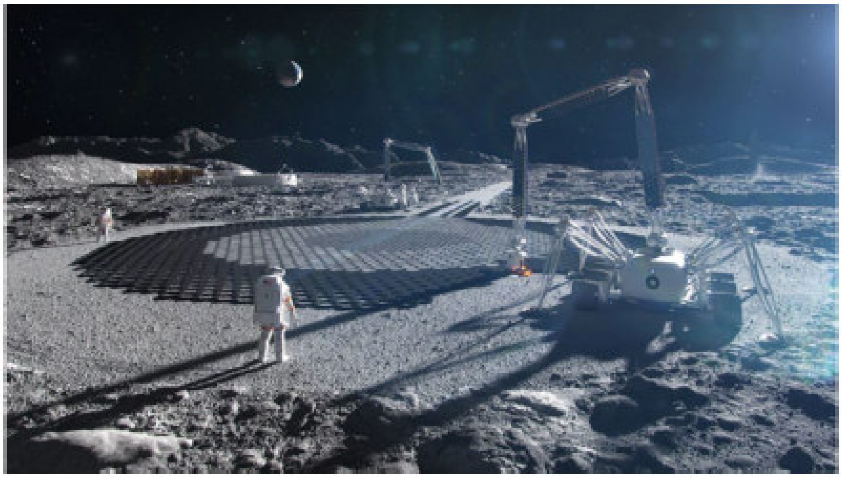


Fig. 256. Artist's conception of additive construction on the moon, courtesy of ICON/BIG-Bjarke Ingels Group

NASA authors have produced a textbook titled *Metal Additive Manufacturing for Propulsion Applications*, published by the American Institute of Aeronautics and Astronautics. The book is intended to serve as an industry and academic resource covering the entire lifecycle of metal AM, from selection through to certification.

AM in the U.S. Department of Defense

by Matthew Friedell

2022 was a tipping point for AM in the U.S. Department of Defense (DOD). The focus on R&D has been reduced, and more attention given to putting the technology into the hands of end users. The Marine Corps and Defense Logistics Agency continue to roll out a large file storage database for end-users to download and print approved parts.

The Naval Information Warfare Center Pacific entered into a Creative Research and Development Agreement with MatterHackers in September 2022. The mission is to identify and resolve military-specific challenges in tactical settings. The team will also evaluate how the military can use open-source 3D printing materials, AM equipment, and commercial-grade technical training.

The U.S. Space Force (USSF), the DOD's newest service, is no stranger to AM. Working with rocketry startup Launcher, the USSF awarded two notable contracts. One was for further development of the company's 3D-printed rocket motor, and the other for an in-orbit servicing module. The contracts are valued at $1.9 million.

The U.S. Navy, building on its partnership with the Naval Postgraduate School and Xerox, installed the first metal 3D printer aboard a ship. In July 2022, a Xerox ElemX 3D printer was installed inside a 20-foot shipping container aboard the USS Essex. In November 2022, an AM installation went aboard the USS Bataan amphibious assault ship. More recently, a Phillips additive hybrid system using a standard HAAS TM-1 CNC, coupled with a Meltio3D wire additive tool, was deployed. It supports the printing of 316L stainless steel, a common metal used on Navy ships.

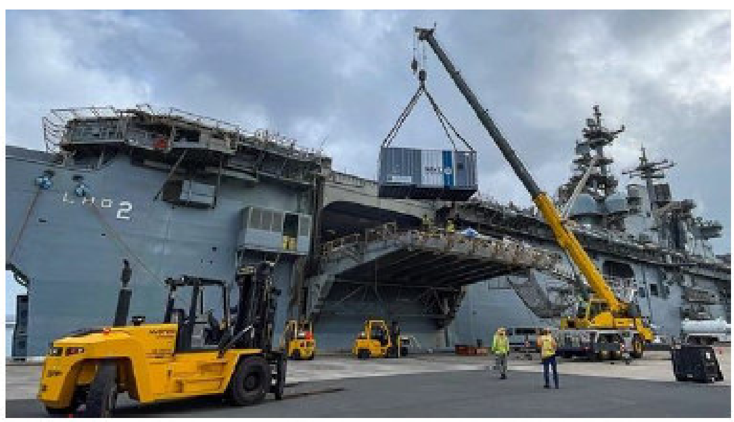


Fig. 257. Xerox 3D printer being loaded onto the USS Essex, courtesy of U.S. Navy

DOD funding of AM continues to increase. The 2023 defense appropriations bill includes $254 million in congressional program increases for AM. This figure does not include other AM projects within individual programs.

U.S. government-sponsored R&D

by John Obielodan

A variety of U.S. federal agencies support AM research. Funding for a wide range of research topics comes from the National Science Foundation (NSF), which funds academic institutions and companies. Other major sources of funding for AM research include the National Institutes of Health (NIH), Department of Defense (DOD), Department of Energy (DOE), and Department of Commerce (DOC). Some awards are made through the Small Business Innovation Research (SBIR) and Small Business Technology Transfer (STTR) programs.

National Science Foundation

This section describes several NSF-funded projects. All were awarded in 2022. Since most NSF projects are two- or three-year awards, this summary represents only the most recent NSF projects. The 2021 and 2022 editions of the *Wohlers Report* include summaries of previously awarded NSF projects; most are still active.

Tennessee Technological University received a Faculty Early Career Development Program (CAREER) award on wire-arc AM of molybdenum alloys for high-temperature applications. The goal is to investigate process-induced residual stress mechanisms, pore generation, and thermomechanical performances of wire-arc AM-processed Mo-alloy structures.

The University of New Orleans received an EArly-concept Grant for Exploratory Research (EAGER) award. It is focused on designing and processing anti-microbial surfaces using polymer extrusion AM to embed silver nanoparticles with enhanced ion-releasing kinetics. The research will investigate how integrated silver nanoparticles, part geometries, and processing conditions influence ion release and its antimicrobial effectiveness on fabricated parts.

The Colorado School of Mines received a CAREER award for research on understanding high-rate AM-deposited nickel-based superalloy microstructures and properties. Project success would support future clean-energy manufacturing.

Temple University received a Boosting Research Ideas for Transformative and Equitable Advances in Engineering (BRITE) award to study thermoelectric materials for AM. The work will investigate specific materials with transverse electrical and thermal properties. The goal is heat transfer within the material perpendicular to the electric field.

Syracuse University received an award for research on ultraviolet (UV) light-induced frontal polymerization in AM and repairing thermoset polymer composites. UV light-induced frontal polymerization is a self-sustaining exothermic chemical reaction and a promising technique for AM of thermoset polymers. It is potentially applicable to fiber-reinforced thermoset composites. The research seeks to understand the mechanisms governing fiber-phase behavior in frontal polymerization through an integrated approach of experimental investigations and computational modeling.

Princeton University received a grant to support research on two-component robotic extrusion of concrete structures. The work includes silicon-solution phases and fiber distributions for functionally graded materials. The aim is to understand the two-component extrusion process in layer-wise robotic AM. The work will investigate the characteristics of fiber-reinforced concrete with silicon containing hydrophilic or hydrophobic compounds for developing tunable functionally graded concrete.

Cornell University received a CAREER award for research on understanding bond formation, microstructural development, and mechanical properties in cold spray AM. The goal is to establish a framework to predict the critical velocity, impact-induced microstructures, micro-scale bond strength, and macro-scale properties of cold-sprayed deposits.

Carnegie Mellon University received an award to investigate the effectiveness of machine learning for supporting engineering designers in rapidly evolving digital manufacturing. The work focuses on AM as representative of the rapid growth and evolution of digital manufacturing. It will combine machine learning, AM, and explainable AI to evaluate the use of automated design feedback from crowdsourced AM design challenges.

San Diego State University received a research award for making high-temperature alloyed parts by combining AM and spark plasma sintering. The research aims to develop net-shaping capability of spark plasma sintering to produce complex parts using difficult-to-fabricate materials.

The University of Michigan received an award to investigate net-shape and scalable AM for thermoelectric waste heat recovery materials using metal PBF. The objective is to develop a novel integrated nanomanufacturing process for high-performance thermoelectric materials and functional devices.

DOD, DOE, and DOC

DOD actively supports R&D efforts in AM through several programs. They include the Defense University Research Instrumentation Program, the Multidisciplinary University Research Initiative Program, and the Defense Advanced Research Projects Agency. The Office of Naval Research, Army Research Laboratory, and Air Force Research Laboratory also fund basic and applied research related to AM. Details on DOD-funded programs can be found at dod.gov.

The following are summaries of SBIR and STTR awards for 2022, funded through the DOD and DOE.

Physical Sciences Inc. received a Phase I SBIR grant to develop additively manufactured ultra-compact heat exchangers for aircraft and pod cooling. It is aimed at meeting the requirements of the Air Force for reliable, lightweight heat exchangers for heating and cooling applications.

Impossible Objects, Inc. received a Phase I SBIR grant to develop personalized lightweight, high-mobility body armor using AM. The company will use its newly developed composite-based AM (CBAM).

Innosek, LLC received a Phase I SBIR grant to develop a novel AM process for making protective radar antenna covers, known as radomes. The objective is to create covers with exceptional durability, capable of withstanding extreme wear and tear, while simultaneously enhancing frequency transmittance. Radomes today are prone to damage from external impact loads, resulting in antennal performance degradation.

Open Additive, LLC received a Phase I STTR grant to work on expanding an AM materials toolbox through novel multi-laser scan strategy development. The research is focused on materials for extreme environments difficult to process using laser-based AM. Ohio State University is the collaborating institution.

TDA Research Inc. received a Phase I STTR grant to develop 3D-printed, modular electronic skin (e-skin) for submersible and scalable tactile sensing. E-skin seeks to mimic the sensory perception of human skin, helping robots to feel and manipulate objects around them. They support the movement of robots through their environment in unstructured, complex pathways. Northwestern University is the collaborating institution.

Birch Biosciences, Inc. received a Phase I SBIR grant to develop enzyme cocktails for mixed plastic recycling. The work aims to develop high-performance enzymes for polyurethane recycling that improves recycling rates of a complex mix of polyurethane products by 100-fold.

Daylyte Inc. received a Phase I SBIR grant to develop thin film Nasicon solid electrolyte membrane for 3D aqueous Na-Air batteries. The goal is to develop a thin, flexible, mechanically, and electrochemically stable Nasicon solid electrolyte that is resistant to highly caustic attack. It will involve the development of a thin-film Nasicon solid electrolyte membrane and the demonstration of the technology in an aqueous Na-Air battery to evaluate lifecycle performance. If successful, it will lead to lighter, faster-charging batteries with a vastly simpler supply chain.

Nanosonic Inc. received Phase I SBIR funding to use AM technologies and materials to develop two related products. The first is bimetallic structures for radio frequency devices. The second is polymer gate valves capable of surviving krad levels of radiation over a two-year period. The work will demonstrate additive and scalable manufacturing methods.

The DOC provides R&D opportunities in AM through several programs. Details on DOC-funded programs can be found at doc.gov.

National Institutes of Health

NIH is a primary supporter of biomedical research in AM. Among the themes for NIH funding are the production of orthopedic implants, coatings, and scaffold structures for biofabrication and tissue engineering. The following are some of the projects awarded by NIH in 2022.

Actuated Medical, Inc. received research funding for patient-specific masks and nasal prongs to improve pediatric ventilation outcomes and reduce pressure sores. The project is in partnership with the Children's Hospital of Philadelphia and Akron Children's Hospital. It seeks to develop processes for manufacturing better-fitting masks and nasal prongs for non-invasive ventilation delivery to younger pediatric patients.

Virginia Commonwealth University received funding for research on mechanisms mediating osseointegration of 3D-printed titanium constructs for dental applications. The goal is to exploit implant physical surface properties to generate new bone in patients lacking sufficient supporting bone without relying on pharmacologic interventions.

U.S. national laboratories

The following three national laboratories are active in AM research and development. R&D conducted at national laboratories is a mechanism for stimulating technology developments and advancements in the U.S.

Oak Ridge National Laboratory

by Kyle Saleeby, Alex Plotkowski, and Thomas Feldhausen

The Advanced Manufacturing Office of the U.S. DOE established the Manufacturing Demonstration Facility (MDF) at Oak Ridge National Laboratory (ORNL) in 2012. The open-user facility performs early-stage research in advanced manufacturing technologies. The overall aim is to improve energy and material efficiency, productivity, and competitiveness of U.S. manufacturers. More than 36,000 individuals and 5,900 companies have visited the MDF, resulting in 230 collaborative research and development initiatives.

The MDF's diverse research portfolio includes development of additive processes, precision machining, sustainable polymer and composite processing, and roll-to-roll manufacturing techniques. Many systems are connected by a digital manufacturing architecture to form a comprehensive Industry 4.0 R&D testbed. A comprehensive metrology and material characterization laboratory is also available. It is used for materials development and cross-disciplinary research support. The MDF seeks to deliver technology breakthroughs to accelerate America's clean, efficient, flexible, and secure manufacturing base.

As a DOE user facility, the MDF is engaged in more than 30 industrial and academic collaborations. This partnership arrangement supports cooperative development of advanced manufacturing capabilities, equipment, and processes, which directly impact the U.S. manufacturing economy. Recent collaborations have resulted in the development of novel manufacturing equipment, such as the Saturn multi-laser rotational powder-bed system. Other developments include a robotic thermoset-based printer capable of out-of-plane printing and a system combining robotics, thermoplastic AM, and compression molding. The MDF continues to be a core partner and technical contributor with many U.S. advanced manufacturing institutes. They include America Makes, IACMI Composites Institute, and the Cybersecurity Manufacturing Innovation Institute.

Working with ORNL's Spallation Neutron Source, MDF researchers developed an open architecture hybrid system that supports real-time neutron diffraction of AM parts. Known as

OpeN-AM, this platform provides an unprecedented understanding of the formation and time history of residual stress in metal AM parts. It offers a direct transfer of knowledge from cutting-edge scientific studies to real-world industrial manufacturing challenges. The project exemplifies the MDF's partnerships with industry, academia, and research organizations to accelerate the development and adoption of advanced manufacturing technologies.

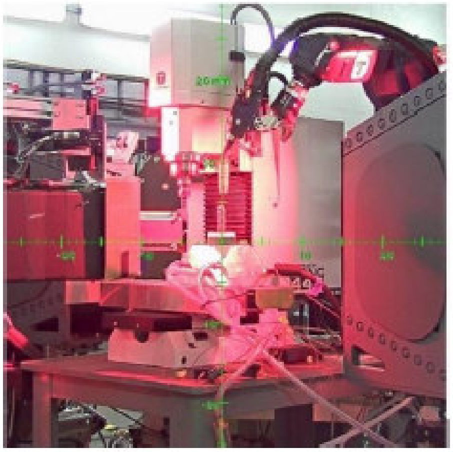


Fig. 258. The OpeN-AM robotic hybrid platform, courtesy of ORNL

Lawrence Livermore National Laboratory

by Chris Spadaccini and Manyalibo Matthews

Lawrence Livermore National Laboratory (LLNL) focuses on AM with an emphasis on national security. Its AM activities include full-scale operation of the Advanced Manufacturing Laboratory (AML) for industry and academic partnerships, and a polymer AM pilot manufacturing facility. The work is performed under the auspices of the U.S. Department of Energy by LLNL under Contract DE-AC52-07NA27344.

AM themes at LLNL include new process and materials development, architected materials, new alloy development, and advancing the understanding and performance of metal AM. It also includes development of new control algorithms, qualification methods, modeling and simulation, design and optimization, and applying machine learning to AM processes. A recent new direction is the development and planned implementation of digital twins for direct-write (DIW) AM systems and laser PBF of metals.

The AML facility is in the Livermore Valley Open Campus (LVOC) outside of the LLNL's main security perimeter. It is designed for advanced manufacturing research and features a reconfigurable chemistry wet lab and a development lab for laser-based AM. Locating the AML in the LVOC makes it easier to partner with industry and academia, both for R&D and technology transfer. It is equipped with AM systems developed in-house, and industry-owned commercial machines for joint projects.

LLNL continues its work on laser PBF of metals. LLNL has six commercial laser metal PBF machines, one open-architecture research machine, and several small process test beds.

Recently, a DED system with a multi-hopper powder delivery system was installed. It is being used to explore rapid alloy screening and functionally graded materials. Simulation and modeling of laser metal PBF continues. Models and experiments are used to study the effect of laser beam shape and thermal history on material microstructure and resulting mechanical performance. In-situ diagnostic techniques based on optical, thermal, acoustic, and X-ray probes are used to gain further understanding and validate models.

Work in process development, architected materials, and multi-functional materials continues. LLNL has matured processes such as projection microstereolithography, DIW, and electrophoretic deposition. Exploration of new material systems, such as glass, biomaterials, composites, and high-temperature ceramics, is also ongoing. Recently invented processes are also under development. Volumetric AM using computed axial lithography has gained momentum with university and industry partners. Work is underway on metal jetting, parallel two-photon polymerization, and other early-stage concepts.

Sandia National Laboratories

by Leah Appelhans and Samuel Leguizamon

Sandia is a multi-mission laboratory managed and operated by National Technology and Engineering Solutions of Sandia, a wholly owned subsidiary of Honeywell International. Operating under contract from the DOE's National Nuclear Security Administration, Sandia has a long history of pioneering AM technology development.

In the mid-1990s, Sandia developed and commercialized laser-engineered net shaping (LENS) and Robocast, an extrusion process for 3D ceramic parts. Sandia has conducted R&D projects valued at about $25 million, with an emphasis on 1) analysis-driven design, 2) materials reliability, and 3) multi-material AM. In response to recent advances in AM technology, Sandia researchers are developing novel materials and innovative AM processing options.

AM of thermoset polymers is typically limited to radical or cationic photopolymerizations and reactive resins, which limits the scope of compatible materials. Recent work in AM of polydicyclopentadiene (pDCPD) using ring-opening metathesis polymerization (ROMP) has resulted in printable thermoset materials with high-performance properties. Sandia has developed new systems for DIW 3D printing of pDCPD resins. These systems address many of the shortcomings of previous 3D printing approaches for ROMP polymers.

Using a photosensitizer/latent catalyst DIW system, the Sandia team has achieved printing rates of more than 60 mm per second (2.4 in per second) for photocatalyzed ROMP of DCPD. Rapid curing enables the DIW process to produce geometrically complex architectures without the need for supports. Also, the living chain polymerization nature of ROMP and high catalyst stability improve inter-layer adhesion, a long-standing issue with material extrusion (MEX) systems.

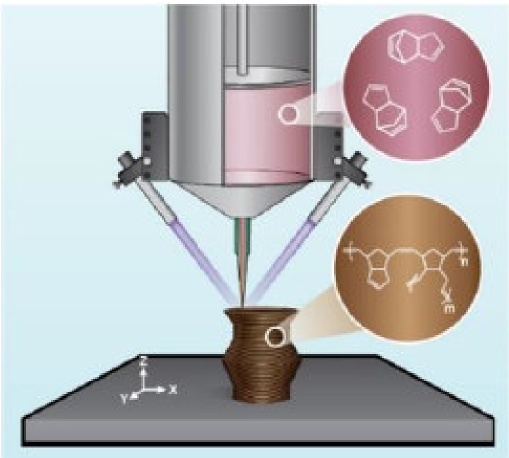


Fig. 259. DIW printing of pDCPD using photo-controlled ring-opening metathesis polymerization, courtesy of Sandia National Laboratories

The Sandia team next investigated VPP of pDCPD due to improved feature resolution. The catalyst/photosensitizer system developed for DIW was modified for VPP to support the tuning of thermomechanical properties, pot-life, activation rates, and irradiation wavelengths. A method for continuous VPP printing of pDCPD using a dual-wavelength approach was demonstrated.

Fig. 260. High-resolution pDCPD parts produced using VPP, courtesy of Sandia National Laboratories

Government-sponsored R&D in Europe

by Giorgio Magistrelli

Research and development programs in the European Union (EU) are supported by public funding at various levels. Funders include the European Commission, 27 member states of the EU, and regional bodies within these countries. More than 30 non-EU member countries are also allowed to participate in EU-funded R&D projects. They include accession countries, candidate countries and potential candidates, members of the European Free Trade Association, and countries covered by the European Neighbourhood Policy.

These funding sources have been pivotal in supporting innovation and development in advanced manufacturing in general and AM specifically. The EU has funded AM research projects as far back as the late 1980s, with more than €400 million awarded between 2007 and 2022.

The following are current EU-funded AM projects. It is not all-inclusive, although it highlights some of the most important ongoing European R&D efforts. Several project names in the table are formal acronyms used to represent longer names.

Name	Years	Description	€M	Coordinator	Country
3D-NANOFOOD	2020–2024	Advancing frontiers in personalized foods for seniors through nanotechnology and 3D printing of enhanced nutrition and superior flavor	0.15	INL	Portugal
ACCESS-3DP	2020–2023	Art & Creative Craft Enterprises for Successful Streaming of 3D Printing	0.35	CMA Auvergne Rhone Alpes	France
ADAM^2	2020–2023	Analysis, design, and manufacturing using microstructures	3.4	BCAM	Spain
ADDress for Future	2022–2024	Additive Manufacturing Training	0.3	BUCOSEV	Turkey
AMANECO	2019–2022	Assessment of AM limits for eco-design optimization in heat exchangers	1.5	Lortek	Spain
AM4BAT	2022–2026	3D printing allows for higher-density lithium-ion batteries	4.85	LEITAT	Spain
AM-TE@CH	2022–2024	Additive Manufacturing academy to boost Trainers' compEtenCes in industry	0.3	KILOMETRO ROSSO S.P.A	Italy
APTIME	2019–2022	Additive Process Technology Integration with Management and Entrepreneurship	0.4	University of Wolverhampto n	UK
AREOLA	2021–2023	Ar/vr foR aErOspace pfb-Lb operAtors	0.25	Favoritanswer	Portugal
ApPEARS	2019–2023	Innovative training for tomorrow's workforce in 2D and 3D Printing	4.3	NTNU	Norway
ASSETs+	2020–2023	Alliance for Strategic Skills addressing Emerging Technologies in Defence	4.0	University of Pisa	Italy
cmRNAbone	2020–2023	3D-printed matrix assisted chemically modified RNAs bone regenerative therapy for trauma and osteoporotic patients	6.3	Ao Research Institute Davos	Switzerland
CNF	2021–2024	Role of microfibrillated cellulose fibers to tune the rheological behavior of fiber-cementitious and fiber-clay mixture for 3D printing application	0.25	Universite De Bretagne Sud	France
DIGIMAN4.0	2019–2022	Digital manufacturing technologies for zero-defect Industry 4.0 production	3.9	Danmarks Tekniske U.	Denmark
DigiWork	2022–2024	Innovative skills to enhance HE students' employability, flexibility, and transversal capabilities	0.38	V-Systems	Poland
DIMOFAC	2019–2023	Digital intelligent modular factories	19.1	Cea	France
DOMMINIO	2021–2024	Innovative digital methodology to design, manufacture, maintain and pre-certify multifunctional and intelligent airframe parts	4.99	AIMEN	Spain
EAGLE	2021–2023	EuropeAn 3d printinG poLymer opErators	0.26	ERACR	Czech Republic

Name	Years	Description	€M	Coordinator	Country
EDURES	2020–2023	Technology education in the digital era supported by the significant use of research results	0.39	Rzeszów University of Technology	Poland
ErgoDesign	2021–2024	Improving digital skills for Ergonomics and Bioengineering Innovations for inclusive Health Care	0.32	Politechnika Poznańska	Poland
FDM^2	2020–2025	Structural multiscale modelling of extrusion-based 3D and 4D printed materials	2.0	UNIBW	Germany
Grade2XL	2020–2024	A 3D printing method for high-performance large structures	9.7	M2i	Netherlands
IDEE	2022–2023	Industrial Design Education Exchange	0.33	CIFP	Spain
IFast	2021–2025	3D-printed copper components for particle accelerators	10.6	Cern	Switzerland
InShaPe	2022–2025	Green Additive Manufacturing through Innovative Beam Shaping and Process Monitoring	0.7	Technische Universitaet Muenchen	Germany
INTEGRADDE	2018–2023	Intelligent data-driven pipeline for the manufacturing of certified metal parts through Direct Energy Deposition processes	12.7	AIMEN	Spain
IP&IE	2020–2023	Technical changes in vocational education	0.18	EBW	Germany
MANUELA	2018–2023	Additive Manufacturing using Metal Pilot Line	15.4	Chalmers Tekniska Hogskola Ab	Sweden
MASTER-STRAINS	2020–2026	European Master in Advanced Solid Mechanics	3.0	Universite De Lille	Lille
METABUILDING	2020–2023	Meta-clustering innovation ecosystem buildings	5.1	Nobatek/Inef4	France
MiniMasonryTesting	2019–2025	Seismic Testing of 3D Printed Miniature Masonry in a Geotechnical Centrifuge	1.99	ETH Zürich	Switzerland
MOAMMM	2020–2023	Multi-scale optimization for AM of fatigue-resistant shock-absorbing metamaterials	3.5	Universite De Liege	Belgium
MULTI-FUN Project	2020–2023	Enabling multi-functional performance through multi-material AM	9.2	Lkr	Austria
NUCOBAM	2020–2024	Promoting additive manufacturing for nuclear equipment components	3.0	CEA	France
OPeraTIC	2022–2026	Boosting the adoption of Ultrashort Pulsed Laser large scale structuring with an agile, dexterous and efficient manufacturing platform	6.1	AIMEN	Spain
PET	2022–2023	Printing Electro-Tomography	0.15	Universiteit Twente	Netherlands
PLANET4	2020–2023	Practical Learning of Artificial intelligence on the Edge for Industry 4.0	0.92	University of Pisa	Italy

Name	Years	Description	€M	Coordinator	Country
PRE-ECO	2019–2024	New paradigm to re-engineering-printed composites	1.47	Politecnico Di Torino	Italy
Print and Grow	2022–2023	A novel support material for 3D bioprinting and post-printing tissue growth	0.15	Technion	Israel
POWERFUSE S	2020–2023	Fusing the gap between 3D-printing and Additive Manufacturing	1.5	Dyemansion Gmbh	Germany
PULSATE	2020–2024	Fostering the PAN-European infrastructure for empowering SME's digital competences in laser-based AM	8.1	Aimen	Spain
PREFAM	2019–2022	European framework for continuous professional development in precision engineering for advanced manufacturing	0.42	Euspen	UK
Re-FREAM	2018–2021	Re-thinking fashion in research and artist collaboration for urban manufacturing	3.9	Creative Region	Austria
RIB-AM	2018–2021	Research of innovative and breakthrough AM concepts	0.6	Fada	Spain
SAbyNA	2020–2024	Simple, robust, and cost-effective approaches to guide industry in the development of safer nanomaterials and nano-enabled products	6.1	LEITAT	Spain
SIRAMM	2019–2023	Eastern European twinning on Structural Integrity and Reliability of Advanced Materials obtained through Additive Manufacturing	0.8	Universitatea Politehnica Timisoara	Romania
SKILLS4AM	2019–2023	Sector Skills Strategy in Additive Manufacturing	3.97	EFW	Belgium
TINKER	2020–2023	Cost- and resource-efficient sensor packaging for autonomous and self-driving cars	10.2	PROFACTOR Gmbh	Austria

Source: Giorgio Magistrelli with help from EC, university, and corporate websites

Most EU projects are funded under Horizon Europe, the successor of Horizon 2020, the European Framework Programme for Research and Innovation. Between 2014 and 2020, Horizon 2020 allocated more than €75 billion in project funding. The Horizon Europe program, which operates from 2021 to 2027, provides about €95 billion in funding. Upcoming funding opportunities, published in January 2023, cover the period 2023–2024.

Beyond EU-funded projects, other AM initiatives are mainly located in southern and western regions, including Germany, France, Italy, and Spain. They include 27 national and 21 regional projects, in addition to one transnational and one transregional project. Several projects in Germany involve the Fraunhofer Competence Field Additive Manufacturing. This alliance includes

18 institutes focused on the development, application, and implementation of AM production materials and processes.

The German Machine Tool Builders Association funds practice-based AM projects. The Mechanical Engineering Industry Association coordinates an AM association supporting its 4,500 members across the entire value chain. France Additive, formerly the Association Française du Prototypage Rapide, has 250 members and directly supports AM stakeholders.

In Italy, the Italian Additive Manufacturing Association has more than 130 members and offers support across the AM industry. The Italian Ministry for Economic Development offers tax incentives for implementing advanced technologies, including AM.

The Additive and 3D Manufacturing Technologies Association of Spain connects about 200 AM stakeholders. Similar initiatives exist in the Czech Republic, Finland, the Netherlands, Poland, Portugal, and Sweden.

After the UK left the EU in 2020, a significant impact on public R&D funding developed. In theory, UK organizations can participate in some aspects of the Horizon Europe program. However, the funding arrangements have not yet been approved. In December 2022, the British government said it would extend research funding support for UK Horizon Europe applicants until March 2023. This support allows them to continue their work while post-Brexit access to European Union science programs is finalized.

Academic activities and capabilities

by Ismail Fidan

AM advancements are occurring rapidly and have been successfully applied in dentistry, defense, and biomedicine. In higher education, almost all fields of study somehow include AM. Programs as diverse as art, engineering, and medicine provide AM-related opportunities to their students in classrooms, studio/clinic settings, and laboratories. University facilities have delivered cutting-edge research and innovative solutions, from developing new products to creating new scientific understanding of AM materials, processes, software, and applications.

Experts from both industry and academia have emphasized AM as a technology for revolutionizing manufacturing. Many engineering schools have implemented AM courses as part of their degree programs. Some academic institutions have also introduced degrees, minors, and short courses in AM to meet demand for an educated and skilled workforce.

Educated and trained individuals are in high demand. Engineering and technology graduates with AM experience and a solid foundation have good career opportunities.

Metal AM technologies have drawn attention and investment from the manufacturing community in recent years. Consequently, several universities have focused their research in this field, while increasing their capabilities in metal AM processes. The number of universities researching wire-arc AM and laser PBF has increased significantly.

Research innovations

Innovations in metal and polymer AM are providing several pioneering solutions to make complex structures lighter, less expensive, and more reliable.

Large-scale construction with the support of AM is one of the emerging research topics. In late 2022, the University of Maine Advanced Structures and Composites Center is said to have 3D-printed the first house made of bio-based materials. Wood fibers and bioresins were used in the construction. The 56-m^2 (600-ft^2) house is fully recyclable. The project was supported by funding from the U.S. DOE's Hub and Spoke program. It involved collaborations with ORNL, MaineHousing, and the Maine Technology Institute.

Auburn University started a project to produce materials and advanced parts for U.S. Army operations. The project is funded by the U.S. Army with a budget of $4.3 million. The goal is to improve American combat readiness. The research group is also planning to apply machine learning toward a better structure-property relationship and to better understand microstructure and defects.

The U.S. DOC's Economic Development Administration awarded a $51.4 million award to Wichita State University. The funds will aid the rapid development and adoption of emerging smart and AM technologies. The project focuses on advancing regional efforts in the effective implementation of sustainable, smart, and AM technologies. It aims to increase competitiveness and profitability of small- and medium-sized businesses, and to increase the region's global market share.

The WAAM research group at Florida International University received a $20 million federal grant, thanks to support from the Florida congressional delegation. The funds will support a project focused on creating custom, durable, and high-performance designs for the Army's next-generation vehicles and munitions.

The University of Sheffield established the Advanced Manufacturing Research Centre North West, a £20-million ($23.9-million) applied R&D facility focusing on large-scale AM. The hub is aimed at maintaining the competitiveness of the UK's advanced manufacturing sector.

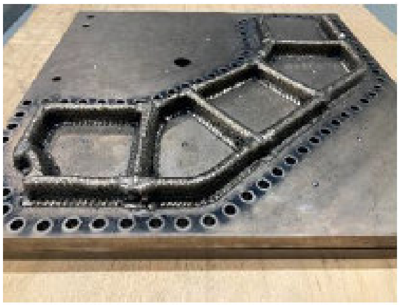


Fig. 261. Bow frame demonstration produced with wire-arc AM, courtesy of BAE Systems and the University of Sheffield

The following pages present summaries of activity at academic institutions worldwide active in AM education and/or R&D. Included are 134 academic institutions, which are listed alphabetically by region. Also, 25 research institutes are listed with a summary of their activities. This compilation does not represent all AM efforts by academic and research institutions worldwide.

Americas

Arizona State University: Due to open in the Fall of 2023, the new School of Manufacturing Systems and Networks will be the first institution in the U.S. to offer bachelor's of science, master's of science, and PhD degrees in manufacturing engineering. Contact: Dhruv Bhate, dpbhate@asu.edu

Auburn University, Alabama: Simulation-, AI-, and nondestructive evaluation (NDE)-based qualification; effects of volumetric and surface anomalies on fatigue behavior; AM materials database (cryogenic to elevated temperatures). Contact: Nima Shamsaei, shamsaei@auburn.edu

Binghamton University, New York: DED, PBF, and hybrid manufacturing; composite and electronics materials; process-structure-property-performance relationships; fatigue testing, multi-physics modeling and simulation. Contact: Fuda Ning, fning@binghamton.edu

Brigham Young University, Utah: Elimination of balling defects and enhancing print speed of BJT; high-speed X-ray imaging of printing under industrial conditions; polymer big-area AM for tooling; non-contact powder bed monitoring. Contact: Nathan Crane, nbcrane@byu.edu

California Polytechnic State University: Facilities include metal PBF, composite MEX, and various polymer and resin-based printing. Research focuses on powder characterization, heat treatment, thin-wall structures, process characterization and optimization. Contact: Xuan Wang, xwang12@calpoly.edu

California State University, Northridge: Generative design and NDE for AM; laser PBF of Haynes 282 alloy for heat exchangers; augmented reality (AR) for metal AM; metal AM for bone and dental implants. Contact: Bingbing Li, bingbing.li@csun.edu

Carnegie Mellon University, Pennsylvania: Laser and electron-beam PBF, BJT, aerosol jet, laser powder stream, wire-arc AM, laser hot wire; materials development and characterization; design, process monitoring, and control; AI applied to AM; robotics in AM; AM minor and master's of science programs. Contact: Sandra DeVincent Wolf, sandradevincentwolf@cmu.edu

Chippewa Valley Technical College, Wisconsin: Establishing project-based learning in the mechanical design program. AM is used to help students optimize designs and evaluate performance using rapid prototyping techniques. Contact: Mahmood Lahroodi, mlahroodi@cvtc.edu

Clemson University, South Carolina: Modeling of AM processes; in-situ process monitoring and prognostics; embedding of sensors into AM parts; AM material testing; printing ceramics and sensors; graduate AM course. Contact: Cameron Turner, cturne9@clemson.edu

Colorado School of Mines: Structural metals and ceramics; process sensing and feedback control; qualification and certification; alloy development; solidification and phase transformations; laser physics; data informatics; design optimization; process modeling. Contact: Craig Brice, craigabrice@mines.edu

Colorado State University: Orthopedic biomaterials; biomechanics; tissue engineering; photopolymers; ceramics; composites; compliant robotics; frontal polymerization; microfluidics; sensors, analytics, lab-on-a-chip; Idea-2-Product 3D printing lab. Contact: David Prawel, david.prawel@colostate.edu

East Tennessee State University: AM lab with 15 MEX printers, two VPP units for prototyping, and one polymer PBF printer for mold making and design optimization; expertise in 3D design, modeling, analysis, and casting. Contact: David Zollinger, zollinger@etsu.edu

Ecole de Technologie Superieure, Canada: Simulation-driven laser PBF process mapping for refractory metals and alloys; damage-tolerant design and computed tomography (CT)-based quality control of laser PBF. Contact: Vladimir Brailovski, vladimir.brailovski@etsmtl.ca

Edmonds College, Washington: Project TEAMM collaborated with Somerset Community College to host a virtual workshop that engaged STEM teachers in new virtual reality (VR) applications and AM concepts. Contact: Mel Cossette, mel.cossette@edmonds.edu

Georgia Institute of Technology: Rapid tooling by hybrid AM; machine learning for AM process control; collaborative robotic AM; high throughput AM materials testing; AM powder recycling and bed quality. Contact: Christopher Saldaña, christopher.saldana@me.gatech.edu

Georgia Southern University: Hybrid AM equipment; 3D bioprinting; low-cost metal AM; PBF test bed design; cellular structures; high-performance materials; in-situ quality control. Contact: Haijun Gong, hgong@georgiasouthern.edu

Indiana University–Purdue University Indianapolis: Collaboration with CCDC Army Research Laboratory and Praxair Surface Technologies on developing thermal barrier coatings deposited on 3D-printed nickel superalloy substrates. Contact: Jing Zhang, jz29@iupui.edu

James Madison University, Virginia: Capacity to perform several ASTM tests: tension and three- and four-point flexure in monotonic and cyclic modes and impact testing. Contact: Rob Prins, prinsrj@jmu.edu

Kansas State University: Kansas State University Salina (Aerospace and Technology Campus) focuses on AM research and teaching space exploration, and applying AM techniques in space. Contact: Mark Jackson, mjjackson@ksu.edu

McGill University, Canada: Laser PBF and DED for microstructure tailoring in non-weldable alloys; powder production and holistic characterization; lattices, part consolidation, AM redesign screening, manufacturability analysis. Contacts: Mathieu Brochu, mathieu.brochu@mcgill.ca and Yaoyao Zhao, yaoyao.zhao@mcgill.ca

Milwaukee School of Engineering, Wisconsin: Rapid Prototyping Consortium is supporting more than 47 companies, each representing a different industry, all focused on application developments, benchmarking, and beta testing of new AM technologies. Contact: Vince Anewenter, anewente@msoe.edu

Missouri University of Science and Technology: Developed novel AM processes for specialized materials, such as steel-copper functionally grade material, glass, high-entropy alloys, and memory alloys; AM for remanufacturing and repair automation. Contact: Frank Liou, liou@mst.edu

North Carolina State University: Materials development for PBF; automated finishing of metal AM parts; process simulation; medical applications; custom implants. Contact: Ola Harrysson, harrysson@ncsu.edu

North Dakota State University: Developing and testing AM systems for short- and long-fiber-reinforced composites with synthesized high-performance thermoset resins and high-fiber volume fractions. Contact: Chad A. Ulven, chad.ulven@ndsu.edu

Ohio State University: Installed 12th metal 3D printer and added a new printing modality for 2023; construction 3D printing with a COBOD BOD II; medical device printing program (M4); advanced polymer printing operations. Contact: Ben DiMarco, dimarco.24@osu.edu

Oregon State University: 3D printing of high-temperature ceramics for hypersonic vehicles, off-gas capture aerogels, and metal-graphene composites. Contact: Dong Lin, dong.lin@oregonstate.edu

Polytechnique Montréal, Canada: Novel non-planar slicing approach; non-planar AM of large aerospace composites; AM of geometry-optimized parts for composite lunar rover; new numerical tools for microscopy image analysis. Contact: Daniel Therriault, daniel.therriault@polymtl.ca

Rochester Institute of Technology, New York: Process development with metal droplet jetting, carbon composite AM; wire-fed hybrid AM, and DIW-printed electronics; DfAM with engineered lattices. Contact: Denis Cormier, drceie@rit.edu

Rutgers University, New Jersey: Laser PBF; wire-fed AM; metal AM; MEX; modeling, simulation, digital twin; process monitoring; finish machining, laser polishing; microstructure tailoring, grain refinement; 3D printing and bioprinting. Contact: Tugrul Ozel, ozel@rutgers.edu

San Jose State University, California: High-resolution laser PBF system from EOS used to manufacture titanium alloy hierarchical bone scaffolds and heat sinks. Contact: Ozgur Keles, ozgur.keles@sjsu.edu

Somerset Community College, Kentucky: Applied AM research and workforce education; high-volume automated AM part production; developing concrete additive construction applications with testing to establish building code approval. Contact: Eric N. Wooldridge, eric.wooldridge@kctcs.edu

Fig. 262. Generatively designed fishing rod holder, courtesy of Somerset Community College

Southern Methodist University, Texas: Development of robotized, laser-based, wire, and powder DED system; development of sensor-fusion-based adaptive process control system to improve AM part quality. Contact: Wei Tong, wtong@lyle.smu.edu

Stanford University, California: Hybrid printing platforms using sound-, light-, and heat-based multi-material printing techniques for medical devices, which are in the phase of clinical translation. Contact: Yunzhi Peter Yang, ypyang@stanford.edu

Tennessee Technological University: Fiber-reinforced AM; mobile AM concept; concrete printing; AM workforce development; low-cost metal AM; wire-arc AM; multi-material printing; quality control; fatigue life prediction of AM parts. Contact: Ismail Fidan, ifidan@tntech.edu

Fig. 263. Lightweight and low-cost anti-germ tools, courtesy of Tennessee Technological University

Texas A&M University: Metal AM team developed an efficient process-optimization framework for laser PBF and DED processes to print defect-free parts and functionally graded alloys. Contact: Ibrahim Karaman, ikaraman@tamu.edu

Texas State University: Applied AM research on atmospheric water generation, including new methods and materials for super-hydrophobic surfaces. Contact: Bahram Asiabanpour, ba13@txstate.edu

University of Akron, Ohio: Multi-material AM for rubber and ceramic materials; multi-scale micro-VPP; ceramic MEX; 3D-printed batteries; normal/shear force sensors. Contact: Jae-Won Choi, jchoi1@uakron.edu

University of Alberta, Canada: Plasma transfer arc AM; wire-arc AM; hybrid AM; rapid solidification; metal/ceramic matrix for AM; AM alloy development; laser PBF; MEX; AM for the energy and mining sector. Contact: Ahmed Qureshi, ajqureshi@ualberta.ca

University of Arkansas: First demo of general-purpose factory with swarm manufacturing; continuous development of microheater array powder sintering and superfast inkjet printing. Contact: Wenchao Zhou, zhouw@uark.edu

University at Buffalo, New York: 3D printing biogenic material (straw) for negative carbon application; 3D printing cybertraining program for cybersecurity education; multi-stage digital manufacturing based on 3D printing and Internet of Things. Contact: Chi Zhou, chizhou@buffalo.edu

University of Campinas, Brazil: New co-working and maker space, which aims to support the development of spontaneous student projects and encourage research and entrepreneurship. Contact: Eder Socrates Najar Lopes, plasma@unicamp.br or ederlopes@fem.unicamp.br

University of Connecticut: Electron microscopy of AM parts and powders; thermophysical property measurements and rapid solidification studies for processing-microstructure analysis. Contact: Rainer Hebert, rainer.hebert@uconn.edu

University of Florida: Research includes process development and modeling; printing with soft and biological materials; post-processing of complex geometries made of superalloys. Contact: Hitomi Yamaguchi Greenslet, hitomiy@ufl.edu

University of Houston–Clear Lake, Texas: Multi-material AM, self-heating composites and molds, reverse engineering with AM, VPP micro-fluid device fabrication, 3D printing of embedded electronics. Contact: Kazi Md Masum Billah, billah@uhcl.edu

University of Louisville, Kentucky: Metal PBF; DfAM; lightweight and cellular structure design; AM workforce training; industrial AM solutions; polymer MEX. Contact: Li Yang, li.yang.1@louisville.edu

University of Maine: Cellulose-based bio-active inks; topology-based lattice structure constructions; process, structure, properties, and performance mapping. Contacts: Bashir Khoda, bashir.khoda@maine.edu and Brett Ellis, brett.ellis@maine.edu

University of Massachusetts Lowell: Multi-material printing; elastomer printing; custom thermoplastic printing; bioprinting; 3D printing of metamaterials. Contact: Christopher Hansen, christopher_hansen@uml.edu

University of New Brunswick, Canada: AM marine applications; microstructure-sensitive DfAM process parameters; heat treatment; advanced electron microscopy; in-situ alloy development. Contact: Mohsen Mohammadi, mohsen.mohammadi@unb.ca

University of North Carolina at Charlotte: Metrology for metal and ceramic AM; in-process monitoring; surface integrity measurements; relating surface topography to subsurface defects; functionally related characterization of surface finish for metal AM parts; ceramic AM. Contact: Harish Cherukuri, hcheruku@uncc.edu

University of North Texas: Center for Agile and Adaptive Additive Manufacturing fosters innovative industry, academic, and government partnerships through science, engineering, education, and training in AM. Contact: Narendra B. Dahotre, narendra.dahotre@unt.edu

University of Pittsburgh, Pennsylvania: Defect detection and simulation; support-structure optimization; fast process simulation; AM-oriented topology optimization (TO); process-structure-property-performance modeling; metal alloy design and development. Contact: Albert To, albertto@pitt.edu

University of Southern California: Multi-scale and multi-material AM process; 3D-printed optics; 3D-printed microfluidic devices; bio-inspired AM structures; bone regeneration scaffolds; energy-related functional device. Contact: Yong Chen, yongchen@usc.edu

University of Texas at Austin: Polymer and metal PBF, AM process control; selective laser flash sintering; multi-material PBF; reactive extrusion; micro-SLS; micro-cold spray; visible light and high viscosity VPP; AM via swarm robotics. Contact: Carolyn Seepersad, ccseepersad@mail.utexas.edu

University of Toledo, Ohio: Metal PBF and BJT of low- and high-temperature shape-memory alloys; functional polymers for machine tools; powder and part characterization; fatigue and composites. Contact: Mohammad Elahinia, mohammad.elahinia@utoledo.edu

University of Utah: Process-structure-property relationship modeling and measurements; surface topography and tribology measurements; high-strain rate deformation experiments; AM-related workforce development. Contact: Bart Raeymaekers, bart.raeymaekers@utah.edu

University of Virginia: State-of-the-art AM facility providing computer-aided design (CAD) and fabrication services to students, faculty, staff, and external clients. Contact: Dwight Dart, dwight@virginia.edu

University of Waterloo, Canada: National AM network with six other universities; holistic optimization of AM processes for advanced materials and applications; accelerated AM modeling. Contact: Ehsan Toyserkani, ehsan.toyserkani@uwaterloo.ca

Virginia Tech: Materials development and multi-physics modeling for polymer AM processes; metal processes in additive friction stir, wire-arc AM, BJT, and PBF; multi-axis toolpaths; multi-material, multi-modal AM. Contacts: Chris Williams, cbwill@vt.edu and Michael Bortner, mbortner@vt.edu

Washington State University: DIW of polymers, composites, and metals; modeling of non-Newtonian ink flow with wall slip; flow-microstructure-property relationships of DIW; learning-based flow rate control in DIW. Contact: Arda Gozen, arda.gozen@wsu.edu

Western Carolina University, North Carolina: The Rapid Center with industry-class AM capacity; engineering services to inventors and regional companies. Contact: Patrick Gardner, pgardner@wcu.edu

Western University, Canada: Distributed recycling and AM for circular economy; open-source hardware, computer vision for smart AM; synthetic images; sustainable development; RepRap. Contact: Joshua Pearce, joshua.pearce@uwo.ca

Worcester Polytechnic Institute, Massachusetts: Feedstock powder and wire development; cold spray and wire-arc AM; metal AM courses; physics-informed AI for AM process modeling, optimization, and control; metal PBF. Contact: Danielle Cote, dlcote2@wpi.edu

Youngstown State University, Ohio: Range of 3D printers for metal, ceramic, polymer, and composite parts. Efforts focused on printing microelectronics and batteries, producing and repairing molds, and sand-casting 3D-printed parts. Contact: Pedro Cortes, pcortes@ysu.edu

Asia/Pacific

Asian Institute of Technology, Thailand: Developing a collaborative large-scale 3D printing system and mobile 3D printers for printing on uneven ground; applying project-based learning and inquiry-based learning to AM. Contact: Pisut Koomsap, pisut@ait.asia

Coimbatore Institute of Technology, India: Developing cost-effective and compact diagnostic tools for retinopathy of prematurity; using multiple AM technologies for a leading eye hospital; ophthalmological aids for a surgical practice. Contact: Rajesh Ranganathan, rajesh.ranganathan@cit.edu.in

Edith Cowan University, Australia: Improving manufacturing quality and mechanical properties/corrosion resistance of titanium alloys and cobalt alloys processed by PBF. Contact: Laichang Zhang, l.zhang@ecu.edu.au

Griffith University–School of Medicine and Dentistry, Australia: Novel material formulation, characterization, and applications; improved performance and sustainable approach in AM; medical devices; national and international collaborations; AM curriculum. Contact: Frank Alifui-Segbaya, f.alifui-segbaya@griffith.edu.au

Fig. 264. Acrylic MEX denture bases, courtesy of Griffith University and Tennessee Technological University

Indian Institute of Technology, Kanpur, India: PBF and DED processes; multi-scale modeling; process development and optimization; metal AM applications. Contact: Arvind Kumar, arvindkr@iitk.ac.in

Jaypee University of Engineering and Technology, India: Mechanical properties of polymer-based porous bone scaffolds; cytotoxic properties of calcium sulphate and polymer porous scaffolds. Contact: Yashwant Kumar Modi, yashwant.modi@juet.ac.in

KLS Gogte Institute of Technology, India: Joining of 3D-printed parts by friction stir spot welding, friction spin welding and microwave welding. Contacts: P. Arunkumar, akp@git.edu and Vivek Tiwary, vgtiwary@git.edu

Nanjing University of Aeronautics and Astronautics, China: Laser AM of metallic components that integrate multiple materials, novel structures, tailored processes, and high performance/multifunctionality. Contact: Dongdong Gu, dongdonggu@nuaa.edu.cn

Nanjing University of Science and Technology, China: 3D printing of metals, ceramics, and polymers; design of novel AM structures; in-situ monitoring and defect control; mechanistic models and deep learning for AM processes. Contact: Huiliang Wei, hlwei@njust.edu.cn

National Institute of Technical Teachers Training and Research, Chandigarh, India: Multi-material metal 3D printing of implants; development of smart materials for 4D printing of thermoplastic composites. Contact: Rupinder Singh, rupindersingh@nitttrchd.ac.in

National Institute of Technology Uttarakhand, India: Research on medical and geospatial AM applications; terrain modeling; physical models of natural World Heritage Sites for conservation management. Contact: Sanat Agrawal, sanata@nituk.ac.in

National Institute of Technology Warangal, India: Corrosion and wear properties of Al-Si samples printed with PBF system for aerospace applications. Contact: Yennam Ravi Kumar, yrk@nitw.ac.in

Nihon University, Japan: Establishment of the Japan Additive Manufacturing Society, which includes all areas of AM. Contact: Masahito Ueda, ueda.masahito@nihon-u.ac.jp

RMIT University, Australia: Fundamental and applied research in TO and materials; manufacturing focused on bioengineering, aerospace, and defense industries. Contact: Milan Brandt, milan.brandt@rmit.edu.au

Swinburne University of Technology, Australia: Cold spray for space and defense applications; simulation of PBF process; energy absorption of AM structures; concrete printing; AM material characterization; laser cladding for AM and repair applications. Contact: Suresh Palanisamy, spalanisamy@swin.edu.au

Tsinghua University - Department of Mechanical Engineering, China: Developed novel electron-beam PBF system equipped with two guns with the same scan area. This approach can provide nonstop preheating and keep the powder bed temperature above 1,100°C (2,012°F) constantly during the build process. Contact: Feng Lin, linfeng@tsinghua.edu.cn

Tsinghua University–Department of Precision Instrument, China: Nanoscale AM of advanced devices and their integrated systems from photosensitive polymers or nanocrystals for micro-optics, micro-electronics, micromechanics, microfluidics, optoelectronics, sensing, biomimetics, and biology applications. Contact: Hong-Bo Sun, hbsun@tsinghua.edu.cn

University of Auckland, New Zealand: DfAM methodologies; triply periodic minimal surface lattices; design automation for heat exchangers, prosthetics, and splints; full-color printing; hybrid tools with conformal cooling. Contact: Olaf Diegel, olaf.diegel@auckland.ac.nz

Waseda University, Japan: Residual deformation reduction of metal laser PBF by laser path and variable lattice density distribution optimization; AM powder damper; metal-plastic hybrid AM. Contact: Akihiro Takezawa, atakezawa@waseda.jp

Xi'an Jiaotong University, China: Innovative research and applications of 3D printing for advanced polymers and their composites, including polyether ether ketone (PEEK), carbon-fiber reinforced PEEK, and multi-functional composites. Contact: Xiaoyong Tian, leoxyt@mail.xjtu.edu.cn

Europe, Middle East, and Africa

Aalto University, Finland: AM sustainability; PBF process monitoring; 4D printing; multi-materials; DfAM; medical applications; multi-material AM; smart parts, spare parts; 3D-printed optics; material modeling, fatigue; hybrid manufacturing. Contact: Mika Salmi, mika.salmi@aalto.fi

Brunel University London, UK: EU-funded projects; AM skills and qualifications; DED; AM standardization; DfAM; and multi-material AM. Contact: Eujin Pei, eujin.pei@brunel.ac.uk

Central University of Technology, Free State, South Africa: Installed first ceramic 3D printer in Africa; significant advancement in mass-customization of 3D-printed titanium spinal implants; first mega-orthopedic implants manufactured in 2022. Contact: Gerrie Booysen, gbooysen@cut.ac.za

Cranfield University, UK: New wire-arc DED process with independent thermal control and demonstration of a 300-kg (661-lb) part. Contact: Stewart Williams, s.williams@cranfield.ac.uk

Gazi University, Turkey: Digital twin for wire-arc AM process, robotic wire-arc AM system; temperature-variance tool path generation for wire-arc AM; evaporation and recoil pressure analysis on electron-beam PBF melt pool. Contact: Oguzhan Yilmaz, oguzhanyilmaz@gazi.edu.tr

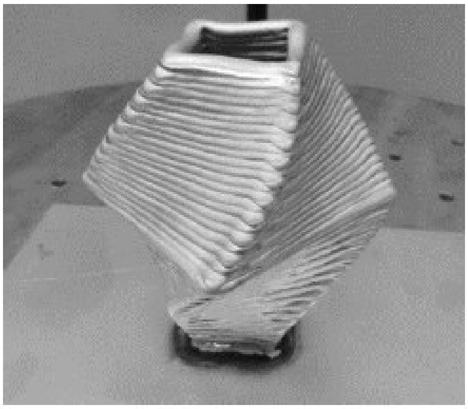


Fig. 265. Spiral vortex cube made using wire-arc AM, courtesy of Gazi University

Heriot-Watt University, UK: Tough polycaprolactone-based biomaterial printable on unmodified desktop DLP printer; 3D-printed microfluidic rotating valves for blood lysate preparation. Contact: Ferry Melchels, f.melchels@hw.ac.uk

Imperial College London, UK: Porosity digital twins using multi-sensor in-process monitoring for quality assurance; alloy and lattice design/optimization; copper powder processing/coating development; wire-arc AM in civil engineering. Contact: Paul Hooper, paul.hooper@imperial.ac.uk

Istanbul Technical University, Turkey: Metal BJT studies; PBF process understanding; AM process modeling; AM graduate courses; two AM student clubs established. Contact: Emrecan Soylemez, esoylemez@itu.edu.tr

Karlstad University, Sweden: Metal PBF of high-performance materials; microstructure and properties (static, dynamic, and tribological) of advanced metal PBF materials; surface integrity, post-treatment, heat treatment. Contact: Pavel Krakhmalev, pavel.krakhmalev@kau.se

KU Leuven, Belgium: Creation of the university-wide, multi-disciplinary Leuven.AM institute with over 200 experts; inauguration of a new AM lab by Crown Princess Elisabeth of Belgium. Contacts: Brecht Van Hooreweder, brecht.vanhooreweder@kuleuven.be and Ann Witvrouw, ann.witvrouw@kuleuven.be

Lancaster University, UK: Design and finite element modeling for AM; electrochemical surface processing; polymer recycling for laser PBF; metal-epoxy composites; smart materials optimization; lightweight polymeric foam structures. Contact: Allan Rennie, a.rennie@lancaster.ac.uk

Loughborough University, UK: DfAM; hybrid AM; custom medical devices; print path control; AM body armor and personal protective equipment; product personalization; printed electronics; 3D printing of art, sculptures, and heritage. Contact: Richard Bibb, r.j.bibb@lboro.ac.uk

Lund University, Sweden: Industrial projects with Alfa Lava, Siemens, Volvo, and Digital Metal; TO; lattice and foam-like structures; DfAM for flexible structures. Contact: Axel Nordin, axel.nordin@design.lth.se

LUT University, Finland: Mechanical properties of metal PBF parts and joints; research on wire-arc AM and wire-laser DED; AM sustainability; memory alloys; business models for AM; simulation of PBF processes. Contact: Ilkka Poutiainen, Ilkka.poutiainen@lut.fi

Luxembourg Institute of Science and Technology: Shape memory electroactive polymer-based composites for MEX filament; bio-based dual curing vitrimers for MEX paste; bio-based resins for VPP. Contact: Joamin Gonzalez-Gutierrez, joamin.gonzalez-gutierrez@list.lu

Machine Tool Institute in Elgoibar, Spain: Five AM technologies for training, R&D projects with universities and technology centers, and technology transfer to SMEs; bound metal deposition process, laser metal deposition/cladding; laser PBF, MJF, and MEX equipment. Contact: Xabier Cearsolo, cearsolo@imh.eus

Mid Sweden University, Sweden: Process and materials development for electron-beam and polymer AM; leading national group with strong industrial network; steel, ceramics, graphene, functional powder and filaments. Contact: Lars-Erik Rännar, lars-erik.rannar@miun.se

Middle East Technical University, Turkey: 3D concrete printing; characterization of composite filaments; implicit design and slicing; rotary rectangular nozzle for MEX; electron-beam PBF characterization; inclined 3D printing; high-entropy alloys; microfluidic applications. Contacts: Ulas Yaman, uyaman@metu.edu.tr

Moscow State University of Technology (STANKIN), Russia: Cold spray and microcladding processes; ion-polishing; thermal fields, heat transfer, laser power density distribution; ultrasonic cavitation; nanoscale powders. Contact: Anna Okunkova, a.okunkova@stankin.ru

Munich University of Applied Sciences, Germany: Process qualification for low-cost steel powder for laser PBF with machine learning approaches. Contact: Christian Seidel, christian.seidel@hm.edu

National Technical University of Athens, Greece: Machine learning for PBF multi-criteria optimization; multi-material PBF powder dispensing; DfAM; FEA of PBF part properties at layer scale; process monitoring by machine vision. Contact: George-Christopher Vosniakos, vosniak@central.ntua.gr

Oslo School of Architecture and Design, Norway: AM applications for industrial design and architecture; developing AM methods for industry and education. Contact: Steinar Killi, steinar.killi@aho.no

Polytechnic Institute of Leiria, Portugal: The first edition of PhD in direct digital manufacturing began in March 2022; the second edition is being prepared. Contact: Joel Vasco, joel.vasco@ipleiria.pt

Ruhr University Bochum, Germany: Metal laser PBF, metal electron-beam PBF; new materials for AM; quality assurance for AM; smart AM parts; sensor implementation; AM process modification; development of point exposure strategies. Contact: Jan T. Sehrt, jan.sehrt@rub.de

Sapienza University of Rome, Italy: Metal powder bed monitoring to correct defects; accuracy study in metal MEX; sustainability of AM processes; aerospace applications of metal PBF; metal PBF process simulation. Contacts: Alberto Boschetto, alberto.boschetto@uniroma1.it and Luana Bottini, luana.bottini@uniroma1.it

Skolkovo Institute of Science and Technology, Russia: VPP-based ceramics fabrication for medicine and ferroelectrics; digital twins of laser PBF; nitinol implants; steel/bronze gradient parts with DED. Contact: Igor Shishkovsky, i.shishkovsky@skoltech.ru

Stellenbosch University, South Africa: Micro-CT scanning for AM quality improvement; structural integrity and effect-of-defect studies; biomimetic DfAM; lattice structures; concrete printing; biomedical applications. Contact: Anton du Plessis, anton2@sun.ac.za

Tampere University, Finland: Multidisciplinary design optimization of AM and DfAM; process-structure-property-performance relationships in digital design to manufacturing; DED processes; smart manufacturing; AM industrialization. Contact: Iñigo Flores Ituarte, inigo.floresituarte@tuni.fi

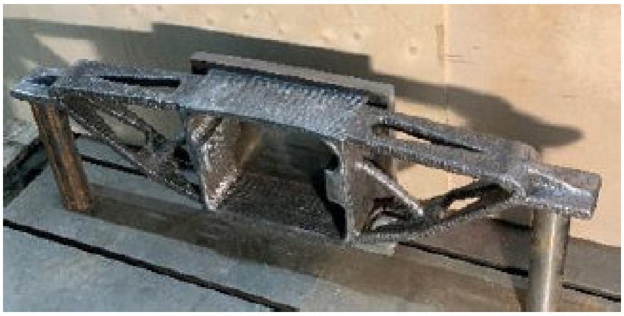


Fig. 266. Topology-optimized multi-material railway bogie replacement (~1 meter long), courtesy of Tampere University

Technical University of Denmark: Research on PBF, VPP, BJT, and industrial adoption of AM; open architecture research platforms; multi-material metal AM; photopolymer slurries; process, material, and monitoring research. Contact: David Bue Pedersen, dbpe@mek.dtu.dk

TU Wien, Austria: With activities in macromolecular chemistry, system development and biofabrication; support of local spin-offs and the global AM community with expertise in photopolymerization. Contact: Jürgen Stampfl, juergen.stampfl@tuwien.ac.at

University of the Basque Country, Spain: Research and training on metal AM; laser PBF and laser DED experimental testing and simulation for aerospace, energy, and automotive industry. Contact: Aitzol Lamikiz, aitzol.lamikiz@ehu.eus

University of Bremen, Germany: AI-supported, recycling-friendly design of multi-material AM parts; automatic generation of strength-optimized joint geometries; vocational AM education and training. Contact: Christoph Leupold, christoph.leupold@uni-bremen.de

University of Cadiz, Spain: Research is focused on mechanical performance of AM processes based on the main process and post-process parameters; material reuse and applied topology. Contact: Ana P. Valerga, anapilar.valerga@uca.es

University of Central Lancashire, UK: Taught graduate program in AM; developed the AMTEx process; facilities include PBF, VPP, micro-VPP, BJT, MEX, hybrid DED AM systems, and 3D scanners. Contact: Hadley Brooks, hlbrooks1@uclan.ac.uk

University of Exeter, UK: Centre for Additive Layer Manufacturing; high-performance polymers, composites, and nanocomposites for PBF and MEX processes using special equipment including EOS P 800 and EOS P 810, 3DGence, Intamsys, and Minifactory. Contact: Oana Ghita, o.ghita@exeter.ac.uk

University of Johannesburg, South Africa: Novel nanomaterials, nanostructures, and Industry 4.0 technology in smart-energy, smart-materials, and smart-manufacturing using atomic layer deposition technology. Contact: Tien-Chien Jen, tjen@uj.ac.za

University of Las Palmas de Gran Canaria, Spain: AM models for training and pre-surgery in the medical field; smart multi-material-graded scaffolds; EDM electrodes by AM; simulation of AM polymer composites. Contact: Mario Monzón, mario.monzon@ulpgc.es

University of Manchester, UK: Toolpath generation and motion planning for multi-axis AM (MAAM); reinforcement by controlling anisotropic mechanical properties of MAAM; design optimization of AM. Contact: Charlie C.L. Wang, changling.wang@manchester.ac.uk

University of Maribor, Slovenia: Aging of PA12 powders in low-cost PBF machines; PBF of magnesium and high-strength aluminum alloys; atomization of aluminum alloys and in-situ alloying of Mg-Al-Zn. Contact: Igor Drstvenšek, igor.drstvensek@um.si

University of Nottingham, UK: Drop-on-demand metal MJT; multi-material processing; lattice design and optimization; reactive MJT of polymers; AM for drug delivery and biodirecting devices; AM of quantum structures. Contact: Mirela Axinte, mirela.axinte@nottingham.ac.uk

University of Oulu, Finland: Statistical analysis of the relationship between AM processing parameters and mechanical properties of AM metals and processes (laser PBF, wire-arc AM, and BJT). Contact: Antti Järvenpää, antti.jarvenpaa@oulu.fi

University of Sheffield, UK: Manufacturing using advanced powder processes; interdisciplinary research, development, monitoring, and control; polymer chemistry; custom alloy development; industrial collaboration. Contacts: Iain Todd, iain.todd@sheffield.ac.uk and Kamran Mumtaz, k.mumtaz@sheffield.ac.uk

University of Trento, Italy: Laser PBF; titanium alloys; cellular lattice materials; structural optimization and fatigue design for AM; defects, notches, and geometrical imperfections. Contact: Matteo Benedetti, matteo.benedetti@unitn.it

University of Turku, Finland: Effect of AM in product design; metal, polymer, and ceramic materials; laser PBF, laser and arc DED; process development with in-situ monitoring and AI; sensor fusion; simulation of AM phases; laser beam-metal interaction; digital twins. Contact: Antti Salminen, antti.salminen@utu.fi

University of Twente, Netherlands: Establishing new, dedicated AM research lab; focus on metals (laser PBF/DED); recent Aconity/Aerosint and Meltio installations; industrial applications with functional and multiphase properties. Contact: Ian Gibson, i.gibson@utwente.nl

University of Western Macedonia, Greece: Optimum design of mechanical systems for AM, considering material non-linearities; analysis/modeling of CAD curves and surfaces for AM applications; mechatronic design for AM-based production. Contact: Nickolas Sapidis, nsapidis@uowm.gr

University of Zanjan, Iran: Research on mechanical behavior of metal AM parts; investigation on residual stresses due to AM processes; development of a new ultra-fast MEX printer. Contact: Rasoul Moharami, r_moharami@znu.ac.ir

Vaal University of Technology, South Africa: Polymer powder materials development; DfAM; AM for metal casting; entry-level AM training. Contact: David Mauchline, davidma@vut.ac.za

Windesheim University of Applied Sciences, Netherlands: Materials, design, and application studies on PBF of aluminum and polypropylene; lightweight end-of-arm tools; undergraduate AM courses. Contacts: Geert Heideman, g.heideman@windesheim.nl and Tommie Stobbe, t.r.stobbe@windesheim.nl

Wroclaw University of Technology, Poland: DfAM, including 3D digitalization; metal alloying in AM; aerospace/automotive/medical applications of AM; monitoring and evaluation of AM processes; AM economics. Contact: Bogdan Dybala, bogdan.dybala@pwr.edu.pl

Research institutes with AM capabilities

The following summaries have been provided by 25 research institutes from around the world. These summaries provide "snapshots" of current research capabilities and accomplishments.

Advanced Digital & Additive Manufacturing Center at Khalifa University, UAE: Patented ideas on additively manufactured thermal management devices (e.g., heat exchangers, thermal energy storage, catalytic converters) based on TPMS stochastic and periodic cellular structures. Contact: Rashid K. Abu Al-Rub, rashid.abualrub@ku.ac.ae

Advanced Manufacturing Center, University of Maine: Industry research with Desktop Metal Studio system and large-format powder-based laser DED system. Contact: John Belding, john.belding@maine.edu

Advanced Manufacturing Research Centre, University of Sheffield, UK: Design for industrial AM; large-scale AM; industrialization of wire-arc AM and friction stir AM; in-situ process monitoring of laser PBF; residual stress management; material/powder characterization; post-processing. Contact: Evren Yasa, e.yasa@amrc.co.uk

AIDIMME Instituto Tecnológico, Spain: Research in processing metals, polymers, nanocomposites, and concrete; laser and electron-beam metal PBF, DED, polymer PBF, VPP, and MEX. Contact: Luis Portolés, lportoles@aidimme.es

AM R&D Center, Tel Aviv University, Israel: Hybrid DED using Optomec LENS machine; new materials design, including alloys, ceramics, composites, functionally graded materials, and coatings, for both civilian and defense purposes. Contact: Vladimir Popov, vpopov@tauex.tau.ac.il

Center for Additive Manufacturing and Logistics, North Carolina State University: Materials development for PBF; automated finishing of metal AM parts; process simulation; medical applications; custom implants; alloy development; material testing; reverse engineering. Contact: Ola Harrysson, harrysson@ncsu.edu

Center for Innovative Materials Processing through Direct Digital Deposition, Penn State University, Pennsylvania: AM design; advanced material systems; process simulation and characterization; technology development and transition; graduate education and outreach;

interdisciplinary R&D; strong ties to DOD and industry; classified capability. Contacts: Ted Reutzel, ewr101@arl.psu.edu, Tim Simpson, tws8@psu.edu, and Allison Beese, amb961@psu.edu

Center of Medical Devices and Additive Manufacturing at New York City College of Technology: Collaborating with the Prosthetic and Orthotic Devices Division in the Hospital for Special Surgery to research and create a custom cover for prosthetic leg. Contact: Gaffar Gailani, ggailani@citytech.cuny.edu

Central Metallurgical R&D Institute, Egypt: Materials and production process research; technical services for design and fabrication of polymer and metal AM products, particularly patient-specific prostheses from titanium alloys and lightweight metal alloys. Contact: Khalid Abd Elghany, kghany@rpcmrdi.org

Ecole Centrale Nantes/GeM, France: Wire-arc AM; hybrid process monitoring; biofabrication; laser metal deposition; PBF; sand printing; numerical simulation; environmental impact assessment; AM sustainability. Contact: Jean-Yves Hascoët, jean-yves.hascoet@ec-nantes.fr

Fraunhofer Institute for Foundry, Composite and Processing Technology, Germany: Multi-material injection-molding insert made from CU-alloy/tool steel built using laser PBF with in-process integrated temperature sensors. Contact: Christian Seidel, christian.seidel@igcv.fraunhofer.de

IDONIAL, Spain: 3D printing of large parts by custom-developed large-format AM technology; 3D printing of technical ceramics for high-performance applications and bioceramics for medical sector; large-scale concrete 3D printing. Contact: Luis Ignacio Suárez Ríos, luisignacio.suarez@idonial.com

I-Form Advanced Manufacturing Research Centre of University College Dublin, Ireland: Development of in-process recommender tool based on AI to provide direct feedback to the operators of laser AM on processing recommendations; 3D printing of PEEK reactors for "tabletop" pharmaceutical plant processing. Contact: Denis Dowling, denis.dowling@ucd.ie

Inspire AG/Innovation Centre for AM, Switzerland: Smart metal parts with integrated sensors and actuators; new open R&D metal AM machine with computer vision and ECT monitoring; new group on direct laser-processing of ceramic powders. Contact: Adriaan Spierings, spierings@inspire.ethz.ch

Institute for Micro Process Engineering, Karlsruhe Institute of Technology, Germany: DfAM in chemical process engineering; design automation for reactors and rectification devices in Power-to-X applications; electrochemistry and fine chemistry; AM process for permeable membranes. Contact: Christoph Klahn, christoph.klahn@kit.edu

Institute of Chemistry and Center for Nanoscience and Nanotechnology, Hebrew University of Jerusalem, Israel: High-performance polymers for 3D printing; 3D-printed ceramics, aerogels, metals, glass, hydrogels, elastomers, wood, drugs, 4D printing, printed electronics, and optoelectronics; soft robotics; water-soluble photoinitiators; bioprinting. Contact: Shlomo Magdassi, magdassi@mail.huji.ac.il

Integrated Additive Manufacturing Center, Politecnico di Torino, Italy: DfAM; process parameters optimization of AM processes; advanced materials development; machine learning; master's program in AM; CT scanning of AM parts. Contact: Luca Iuliano, luca.iuliano@polito.it

Israel Institute of Metals, Technion–Israel Institute of Technology: PBF and BJT for R&D of new metal alloys, functional materials, tungsten alloys, graphite structures, shape-memory alloys, and composites for aerospace and biomedicine; polishing and joining techniques. Contact: Evgeny Strokin, strokin@technion.ac.il

Maoz Lab, Tel Aviv University, Israel: 3D printing of polymers; 3D bioprinting (cells and gels); developing advanced human-relevant models for studying human physiology by 3D printing "Organs-on-a-Chip" and by 3D printing tissues. Contact: Ben Maoz, bmaoz@tauex.tau.ac.il

National Center for Additive Manufacturing Excellence at Auburn University, Alabama: Structural integrity; qualification and standardization; integrated computational materials engineering; AM of lattice structures; additive nano-manufacturing; micro-/defect-structure-property relationships; AM applications. Contact: Nima Shamsaei, shamsaei@auburn.edu

NSF IUCRC Center for Science of Heterogeneous Additive Printing of 3D Materials, Massachusetts: Collaborative research center between industry and universities; multi-material, photopolymer, MEX, composites, elastomers; defect detection, born-qualified, and toxic reduction. Contact: Joey Mead, joey_mead@uml.edu

Occupational Hygiene Health Research Initiative, North-West University, South Africa: Monitoring and reducing exposure to AM operators from potentially hazardous AM materials; providing industry-relevant controls to protect AM operators. Contact: Sonette du Preez, dupreezsonette@nwu.ac.za

Singapore Institute of Manufacturing Technology: Powder reusability; tuning microstructure by process control; new materials development for AM; AM of parts made in γ-TiAl and Ti-6Al-4V; distortion discrepancy of large parts with electron-beam PBF processes. Contact: Wang Pan, wangp@simtech.a-star.edu.sg

Sirris, Belgium: AM-specific material development (magnetic, pure copper, loaded polymers); AM-oriented powder characterization; AM monitoring data consolidation; automatic defect detection (computer vision in AM); AI-powered material parameter set definition. Contact: Olivier Rigo, olivier.rigo@sirris.be

VTT Technical Research Centre of Finland: R&D in aerospace, energy, and e-mobility applications; novel applications and materials, including embedded intelligence, quality monitoring, and magnetic materials. Contact: Sini Metsä-Kortelainen, sini.metsa-kortelainen@vtt.fi

PART 7: THE FUTURE OF ADDITIVE MANUFACTURING

Advancements suggest optimism

by Gianluca Mattaroccia and Ray Huff

Significant mergers and acquisitions, large investments, and restructuring of additive manufacturing (AM) companies occurred in 2022. Consolidation has been widespread across system manufacturers, software developers, material producers, and service providers. Several large AM players have grown larger. As examples, 3D Systems acquired Titan Robotics, and Markforged purchased Digital Metal. AM software companies also found new owners, such as AM system manufacturer Carbon acquiring Paramatters. Large AM software provider Materialise acquired Identify3D. Even long-time rivals MakerBot and Ultimaker united in the desktop 3D printing space.

New applications are emerging as a result of these acquisitions. Future consolidation is expected to advance the AM industry by penetrating deeper into developing and established sectors. Veteran 2D printing company Epson entered the 3D market, unveiling an AM system that uses both filaments and pellets. Optics giant Nikon acquired metal AM system producer SLM Solutions and made notable investments in Optisys and Hybrid Manufacturing Technologies. In the long term, the AM ecosystem will expand and mature to stand alongside established manufacturing processes such as injection molding, casting, and machining.

Service providers with impressive capabilities across the AM value chain are also consolidating. Many of these maturing companies are working with customers to advance their know-how in design for AM (DfAM) and series production. The result is the production of end-use products in aerospace, healthcare, energy, and consumer goods. Recent advancements suggest it will expand into other sectors in the foreseeable future. Examples are the 3D printing of food, medicine, and electronics.

An increasingly digitized global economy increases the value of the digital-to-physical nature of AM. It can help mitigate supply chain gaps by supporting on-demand and point-of-sale manufacturing. Other positive impacts of AM include a potential reduction in shipping costs, lead times, and inventories of goods. Local manufacturing is also becoming a priority for many governments. The U.S. White House launched the AM Forward initiative to stimulate use of the technology in American industry.

A trend toward distributed manufacturing is expected as AM improves automation, productivity, sustainability, and a return on investment. Initiatives are underway to better use the earth's natural resources, such as some lean AM processes. Breakthroughs in the use of reclaimed feedstocks unlock added incentives, such as Epson Atmix and Continuum's use of recycled metal to produce AM powder. Chemical producer Evonik has implemented a process to make polyamide powder with a reduced carbon footprint. Increasing demand for a greener lifestyle may well push AM into the forefront of production in the future. The adoption of AM will continue to grow as consumers realize legacy manufacturing processes often produce higher waste and unwanted by-products.

Technical directions and trends

AM has long depended on its users to identify new ways to use the technology. User ingenuity is a powerful force for innovation, as strong as an inventor's original ideas. The future will be shaped by the meeting of these two tides progressing the technology in tandem. AM powder-user Jabil is offering a new AM powder based on its own experience with the limitations of common polymer feedstocks. Massachusetts Institute of Technology has repeatedly contributed to the advancement of AM. The university spun off VulcanForms to develop large-format metal powder bed fusion (PBF) systems. Seeking to improve the speed of metal AM, startup Sun Metalon continues to raise capital to develop its novel system that heats metal by layers instead of by points or lines.

AM continues to contribute significantly to part production when multi-functional performance is required. With part consolidation using DfAM techniques, a single part can perform several functions, such as fluid flow control, load transfer, and locations for product assembly. Parts designed for AM can reduce weight, complexity of manufacturing, and assembly costs. Heat exchangers, for example, are conventionally produced from many parts to maximize surface area and thermal transfer. Using methods of DfAM, companies such as Conflux and GKN Additive are developing efficient heat exchangers with fewer parts.

AM's presence is strongly felt in the aerospace industry. The U.S. Space Force awarded a grant to Launcher to use AM to create rocket engines. The technology has been a stepping stone toward affordable rocket engine production for companies including SpaceX and Relativity. UK-based Orbex raised over $40 million to scale up its two-stage rocket designs.

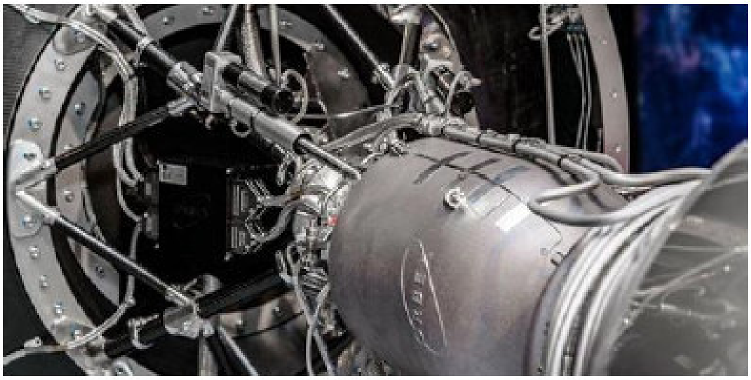


Fig. 267. AM-enabled two-stage rocket, courtesy of Orbex

A long-term goal of space travel is to print parts on-site. Many teams are researching AM to produce buildings, launch pads, and other facilities on uninhabited planets. One possibility is to use local raw materials as feedstock. NASA funded additive construction (AC) company ICON to develop construction methods and technologies for off-world use.

Shell is the first oil and gas company in Europe to obtain CE certification from a third-party authority for an in-house AM part. The part is a pressure vessel manufactured with PBF at the Energy Transition Campus in Amsterdam. Shell worked with LRQA to certify the part in accordance with the European Pressure Equipment Directive. This certification is an important milestone for the oil and gas industry because no legislation or global standards are yet available for 3D-printed pressure vessels.

In February 2023, California's Sakuú began manufacturing 3D-printed solid-state batteries in custom shapes and sizes. According to the company, its AM-produced batteries have the same power capacity as lithium-ion batteries at half the size and one-third the weight. 3D-printed batteries may penetrate other markets, including aerospace, miniature medical devices, and personalized consumer electronics.

Software companies are opening new horizons of DfAM through novel software techniques. Implicit modeling and field-driven design are being used in the aerospace and automotive industries. For example, these approaches advance heat exchanger design by leveraging algorithms for computational fluid dynamics. Such designs add complex and highly efficient shapes and features not manufacturable without AM.

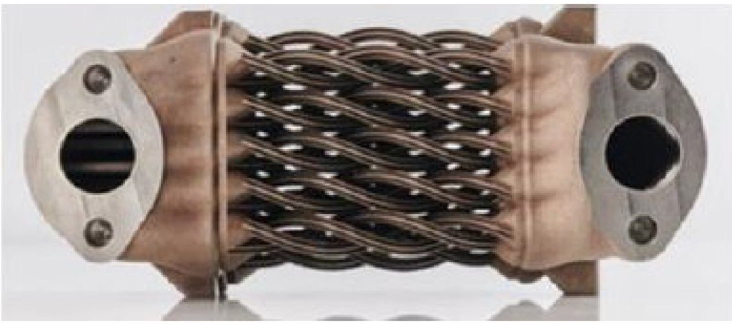


Fig. 268. Advanced heat exchanger design, courtesy of the Manufacturing Technology Centre

Other companies are pursuing more intuitive ways of converting design concepts into solid models in software. French company Spare Parts 3D is collaborating with the French Defense Innovation Agency to develop workflows that produce AM-ready models from 2D designs. Axial3D received financial support from Stratasys to develop medical-targeted software along a similar vein.

Materials such as silver, copper, and gold can be difficult to print using laser PBF systems. These metals have high reflectivity in the near-infrared spectrum range, but this can be circumvented by substituting lasers that operate in the visible spectrum. Green lasers operate with a reduced wavelength and can print parts with high electrical and thermal conductivity. Material developers, such as HRL Laboratories, have developed alternative methods. One approach is to include additives that enhance the metal's printability using standard lasers. These developments expand the spectrum of AM systems and materials.

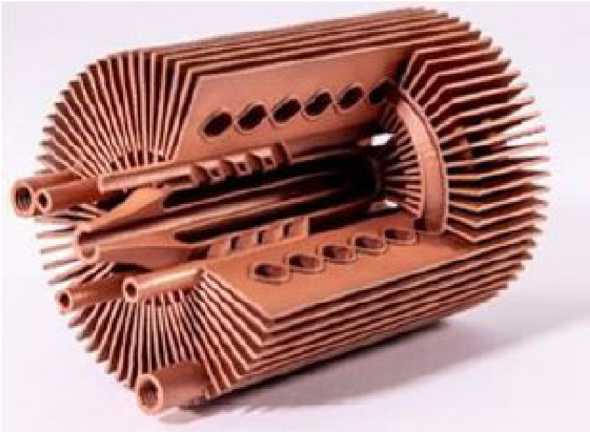


Fig. 269. Heat exchanger made of copper, courtesy of Delva

The use of AM applications for personalized healthcare will grow even more quickly if parts can change form and adapt to environmental conditions. When AM is used to create these parts, it is sometimes referred to as 4D printing.

In 2022, BellaSeno announced that its bioresorbable breast implants had begun human trials. The 3D-printed implants are designed to guide tissue growth as it is absorbed by the body. Later in the year, the U.S. Department of Veterans Affairs received FDA clearance to use 3D printing to assist in surgical procedures. In New York, regenerative medicine company 3DBio Therapeutics announced the successful implanting of a 3D-printed ear produced using the patient's own cells.

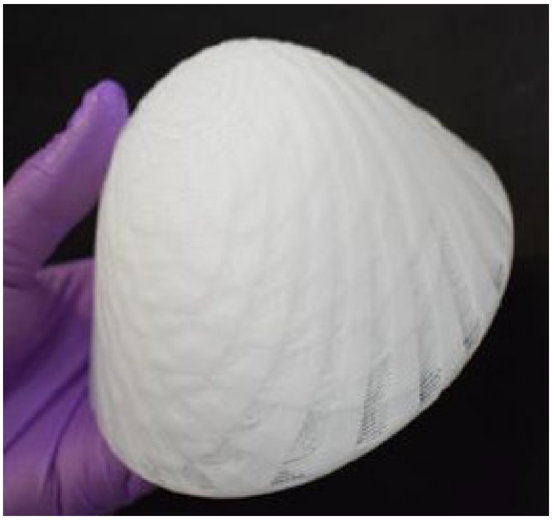


Fig. 270. Bioresorbable breast implant, courtesy of BellaSeno

In 2022, 3D Systems continued expanding its medical AM capabilities by acquiring Kumovis and its biocompatible 3D printer technology. Stratasys received class II FDA clearance to make dentures using AM. Many companies announced collaborations to advance 3D-printed pharmaceuticals. Among them are Aprecia, Curify Labs, Eli Lilly, Natural Machines, and Triastek. Aprecia was the first to receive FDA clearance for a 3D-printed medicine. In 2015, it commercialized SPRITAM, also known as levetiracetam, a drug used to help control certain types of seizures.

The global automotive market continues to pioneer the use of AM for production applications. In early 2022, General Motors announced plans to produce the Celestiq, its flagship electric Cadillac vehicle. GM is on-shoring more than 100 3D-printed parts. The company maintained on-time delivery of the production of the Chevrolet Tahoe using 60,000 AM parts. Divergent Technologies began using AM to produce aluminum sub-frames for Aston Martin.

Developing countries benefit from the agile nature of AM by supporting production with limited supply chains. The Indian government has announced its intention to deploy as many as 100 new AM-related startups to bolster its economy. Dassur of Saudi Arabia partnered with 3D Systems to stimulate the use of AM in the Middle East. Amaero and Rabdan established a joint venture to produce AM parts and powders at a forthcoming plant in Abu Dhabi.

Innovative use of AM continues to grow. Lacrima Foundation caused a buzz with its 3D-printed beehives, designed to restore natural bee habitats. Seaboost Ecological Engineering led the deployment of a 3D-printed concrete reef off the coast of France. The structure weighs more than 100 tons and will lighten the burden of diving traffic at sensitive natural reefs. Mycorena of Sweden and Revo Foods of Austria announced a joint initiative to produce fish products by 3D printing proteins.

Challenges ahead

Many technical changes and advancements are underway. They are coupled with a widening skills gap and an increasing number of technical manufacturing jobs. Other issues are the retirement of the "baby boomer" generation and the Great Resignation involving an estimated 33 million Americans who quit their jobs, mostly in 2021. This has further increased the number of high-tech positions and a need for people to fill them.

Employers responded to these conditions by adjusting pay and benefits to attract new talent. Continued job market turmoil puts pressure on companies hoping to maintain a skilled workforce. Beginning in mid-2022, Carbon, Desktop Metal, Nexa3D, and others downsized by laying off scores of employees. AM service provider Fast Radius filed bankruptcy in November 2022, and its assets were purchased by Sybridge of Michigan for a fraction of its estimated value.

Insufficient training and education are major challenges expected to become more severe in the short term. An estimated two million manufacturing jobs will go unfilled in this decade in the U.S. alone. The job market in AM is growing, but trained and experienced personnel are needed to fill them. Technical schools, community colleges, and universities are challenged to expand educational opportunities in AM. More than ever, professional societies, associations, and standards development organizations are faced with expanding their training and certification programs.

The use of AM for series production in automotive and electronics is limited, but growing. Organizations are working to address AM's high production costs and limited range of materials. To a degree, this challenge can be overcome with the use of low-cost AM systems capable of producing quality parts coupled with inexpensive feedstock. Low-cost AM systems offer impressive material choices and print resolutions that rival more expensive systems. It remains to be seen whether they will become as acceptable as industrial AM systems.

Conventional computer-aided design (CAD) has limited features for generating geometrically complex designs suited to AM. DfAM is an approach and not a CAD product one can buy. The current cost and complexity of specialized design software tools are barriers to adoption. The design workflow for AM could benefit from simplification and more integrated functionality. A combination of software products is often required to design and prepare parts for 3D printing. Many designs that hold closely to suggested workflows still fail due to the intricacies and hidden limitations of AM processes. Increased standardization, research, and discovery will continue to pave the way toward progress for the AM community.

Automated AM production

As detailed in Part 4 of this report, for more than a decade, AM has increasingly been used beyond its initial application as a prototyping tool. However, a continuing limitation to adoption for final parts is the time factor. AM builds can take many hours to finish, then require cooling, post-processing, and other manual steps. Automating these steps can maximize production capacity, minimize hands-on processes, and lower production costs. Companies determined to optimize AM's production capacity are dedicating time and energy to automation initiatives.

In 2019, a consortium of 12 industry and research partners launched the Industrialization and Digitalization of Additive Manufacturing (IDAM) project. In 2022, the Fraunhofer Institute for Laser Technology reported that IDAM has met its goal of producing more than 50,000 parts per year using laser PBF. The project has led to the integration of digitally networked and fully automated AM processes into the German automotive industry.

Funded by the German Federal Ministry of Education and Research, IDAM made it possible for the BMW Group to expand future series applications for AM. The project involved setting up a digitally connected, fully automated 3D printing production line at the Additive Manufacturing Campus in Oberschleissheim. The production line was designed to support 24/7 production and to demonstrate a high level of economic efficiency.

As part of the project, new concepts were developed for automated generation of AC data. Powder preparation and post-processing are both fully automated. Quality assurance of the finished parts is performed in-line, during the laser melting process, using sensors. This includes checking emissions from the molten pool with a complementary metal-oxide semiconductor (CMOS) camera and pyrometer. Artificial intelligence (AI) algorithms are used to correlate the data collected with known component quality.

Fig. 271. Elements of the IDAM project at BMW Group, courtesy BMW

The international Formnext 3D printing conference in Frankfurt resumed in-person attendance in November 2022. Several companies presented new or notable AM automation products. KraussMaffei displayed its large vat photopolymerization (VPP) system. It combines material handling, part washing, and curing in one semi-automated machine. The company expects the system to provide improved throughput, efficiency, material handling, and safety.

Print & Go displayed its automated part removal solution for material extrusion (MEX) print clusters. Prusa Research and Mosaic have also developed small print farm solutions made up of a handful of desktop 3D printers in a cabinet. The systems automatically remove print beds after each build and store them for operator retrieval. Pro-beam Group announced a build box exchanging system called BuildUnits that improves the productivity of its PBF machines. With BuildUnits, a new build can start while the previous build is cooling, increasing the AM system's uptime.

Fig. 272. Robot arm for removing AM parts, courtesy of Print & Go

Emerging applications

Developments in recent years are leading to interesting new applications of AM. A growing number of organizations are developing systems that can 3D print electronics, food, and medicine. Each one could grow to become significant in the future.

Electronics

3D-printed electronics is a specialized field. In contrast to many other AM applications, printed circuit boards (PCBs) require the deposition of two very different materials—one conductive and one non-conductive. Developments in AM materials and processes over the past decade have contributed toward advancing this application.

The printing of sensors and antennas is possibly the most developed application. For years, companies have done both in production settings. For example, a manufacturer in Asia has been 3D printing antennas into the frames of mobile phones at high speeds using the Aerosol Jet process from Optomec. Using the same technology, manufacturers are printing sensors into parts, such as turbine blades produced by GE, to measure stress, fatigue, and wear.

Fig. 273. Simultaneous printing of antennas into the frame of four mobile phones, courtesy of Optomec

The process from Nano Dimension can produce PCBs with substrate, conductive traces, and passive components generated in a single step. The company claims this method increases design flexibility and reduces lead time. It also claims the elimination of toxic waste and reduced energy consumption compared to conventional manufacturing. Companies are using this technology to produce prototype electronic devices. Research is needed to improve the reliability and efficiency of the PCBs.

Food

by Kjeld van Bommel

As 3D food printing (3DFP) continues to develop and more applications are investigated, new products are emerging. Initial applications of 3DFP focused on the creation of unique shapes and designs. More recently, interesting possibilities have been investigated for the creation of specific textures and personalized compositions. This has resulted in the development of new 3D-printed food products and applications.

MEX is the most widely used process for 3DFP because it can support a wide range of formulations already used in the food industry. They include pastes, doughs, and purees. One existing application is 3D-printed pasta marketed by BluRhapsody. The company recently added dried 3D-printed pasta shapes to its product portfolio, along with frozen pasta.

3D-printed chocolate is available from Callebaut and Mondelēz, and 3D-printed candy is produced by Katjes Magic Candy Factory. Moving away from MEX technology, the BJT machine sold by Currant 3D produces full-color designer food products. French startup La Pâtisserie Numérique produces 3D-printed pastry products using a powder bed process.

Fig. 274. 3D-printed food objects, courtesy of Currant 3D

Other applications have emerged that benefit from the different materials and ingredients that 3DFP can accommodate. UK company Nourished continues to work with partners to develop personalized nutraceutical products. They include a candy containing ingredients that promote oral health, developed with Colgate, and a new personalized protein bar product line.

Dutch startup Gastronology 3D Food Works is launching a range of 3D-printed vegetable puree products in 2023. The products are aimed at people suffering from dysphagia (i.e., the inability to chew and/or swallow regular foods). People with this condition are currently restricted to eating shapeless purees similar to baby food. By printing the pureed foods into attractive shapes, the enjoyment of eating returns. An additional market opportunity is focused on children who will not eat vegetables but are attracted to broccoli dinosaurs.

The application of 3DFP to meat and fish replacement products continues to develop. Aleph Pharm, Novameat, Revo, and Steakholder Foods are all developing 3D-printed food products using either plant-based proteins or living cells taken from an animal. Israeli startup Redefine Meat launched its first 3D-printed whole-cut meat replacement product in 2021. The product mimics a steak and is produced using three different printing formulations, one each for muscle, blood, and fat.

Fig. 275. 3D-printed steak replacement, courtesy of Redefine Meat

3D-printed food is currently used to create niche products that are mostly sold at high prices. Scaling this technology and creating cost-competitive products and business models remains a challenge. This is a focus of the Digital Food Processing Initiative (DFPI) collaboration, which demonstrated a patented extrusion-based multi-nozzle printer in 2021. The collaboration claims the printer's modular architecture could open opportunities for large-scale production of 3D-printed food products.

Medicine

by Anton Aulbers

3D-printed medicine (also known as 3D pharmaprinting) is attracting increased attention in the medical and pharmaceutical world. AM supports the printing of tablets with specific drug loads and easily tunable release behavior in a decentralized and flexible way. This resonates with other developments in the medical world toward increasingly personalized medication. It also has the potential to provide new treatments and solutions for unmet clinical needs. The pharmaceutical industry recognizes the potential of AM to speed the development of new medications. The technology also supports the fast and flexible production of pills and tablets for clinical trials.

Increased interest in 3D-printed medicine has led to a sharp rise in the number of related scientific research articles and publications. They cover not only technical and medical possibilities, but also implementation-related issues such as regulatory acceptance and quality monitoring.

University College London and its spin-off, FabRx, have been active in this field. Developments are also coming from traditional pharmaceutical suppliers such as DFE Pharma, Glatt, and Merck. The most widely researched AM process for 3D-printed medicine is MEX. The use of semi-solid extrusion (SSE) to produce small-series personalized medication is attracting interest. Several startup companies are working on dedicated SSE equipment to be used for 3D pharmaprinting.

China's Triastek has been working to scale its Melt Extrusion Deposition (MED) technology and has opened a production facility in Nanjing. The company has announced a joint research project with Millipore-Sigma on dedicated excipients for MED. Several experimental drugs are under development. In November 2022, the FDA gave Triasek clearance for clinical trials of a 3D-printed drug for ulcerative colitis.

Several research hospitals are exploring the possibility of local 3D printing of personalized medication for patients. One example is the Erasmus Medical Center in the Netherlands. The center has partnered with TNO and several companies to work on SSE of tailored heart medication for small children.

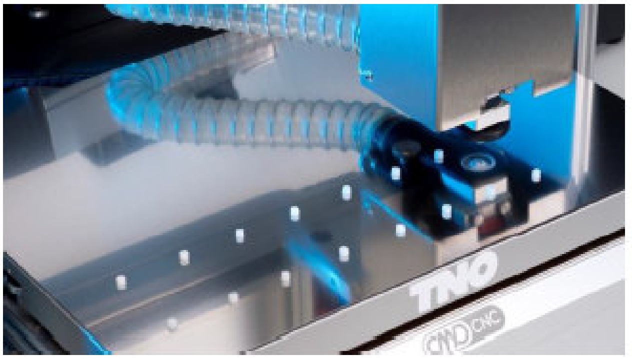


Fig. 276. Semi-solid extrusion printing of medication for children, courtesy of TNO

Widespread adoption of 3D pharmaprinting requires further innovation in several areas. They include cost efficiency, quality monitoring, and compliance with strict regulations.

Other areas

Many AM systems manufacturers are producing machines with large build volumes. This is partly due to the demand for increased throughput and reduced part costs. Some manufacturers are directly targeting the market for large parts. Applications in which large parts are particularly beneficial include advertising displays, large forming tools, and movie props.

Some advertising or media campaigns require the production of large physical models. Israeli company Massivit 3D offers a range of MEX systems with large build volumes. Target markets include transportation, entertainment, and visual communications. Massivit customers use this technology to create high-impact advertising displays. Adidas promoted a special edition Terry Fox 40th Anniversary running shoe with a large model. The shoe model was printed on a Massivit machine and finished to a high level of detail.

Fig. 277. 3D-printed Adidas shoe model, courtesy of Massivit 3D

Using AM to produce large forming tools can save time and money, according to Additive Engineering Solutions (AES). The following image shows a tool used for high-temperature composite layup of a carbon-fiber-reinforced polyether sulfone aircraft part. The tool was produced on a big-area AM (BAAM) polymer MEX system and finished on a CNC machine. Making this tool using conventional methods would have been more expensive and time consuming, AES claims. The tool would have otherwise been made in a composite material using a machined foam master or fabricated from metal sheets welded together and then machined. With AM, the tool was built to within 9.5 mm (0.37 in) of net shape in about 24 hours. This resulted in a reduction in CNC machining time.

Fig. 278. Large forming tool, courtesy of AES

The production of props for movies, television programs, and other film and studio applications is another area where large build volumes are making an impact. Examples provided by Jason Lopes of Gentle Giant Studios demonstrate the value of full-scale and large models of characters and scenes. A 2.4-m (8-ft) maquette of the White Dragon on top of Gringotts Bank (from the Harry Potter movies) was produced for Universal Studios. A full-size sculpture of The Collector character from Marvel Cinematic Universe was built using a ProX 950 machine from 3D Systems. After painting, the sculpture was put on display at Disney's California Adventure Park. A similar project involved creating a full-size Spiderman model for display at the Museum of Pop Culture in Seattle.

Fig. 279. Large-scale 3D-printed models, courtesy of Gentle Giant Studios

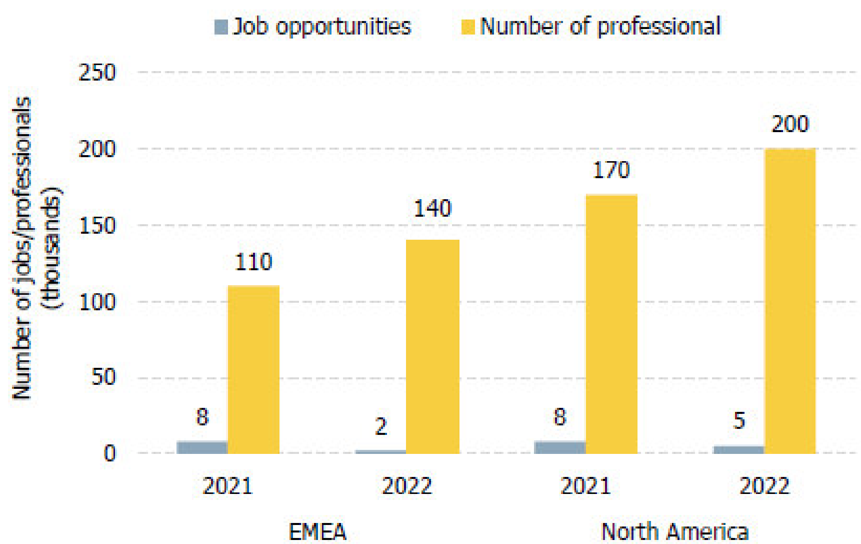
Workforce development

by Nick Pearce

2022 has been one of the busiest years to date in the AM talent and job market. This is particularly true where hiring is concerned. Corporate AM placement specialist Alexander Daniels Global (ADG) made 32% more placements in 2022 than in 2021. Hiring was expected to decline in 2022, following the Great Resignation in 2021. However, talent requirements increased as the industry withstood this difficult time.

Studies conducted by ADG found workforce growth in 2022. In North America it found a 17.6% increase in AM professionals, while the European, Middle East and African (EMEA) region experienced a 27.3% increase. ADG found zero growth in 2021 in EMEA, so the industry is in a much healthier position in 2023. Conversely, job opportunities have decreased in both markets, with reductions of 40.1% in North America and 75% in EMEA. This translates to a candidate-to-job-opening ratio of 15:1 in the U.S. and Canada and 23:1 in EMEA for 2023.

Fig. 280. Available job opportunities versus number of AM professionals by year in North America and EMEA; source: Alexander Daniels Global



Major layoffs occurred across the industry in 2022, flooding the market with experienced AM talent. Historically, situations like this have caused a short- and long-term effect on the talent market. Employers took on new talent quickly to the detriment of "best fit" and adequate pay. This resulted in increased movement in the talent market in the medium term.

In 2022, industry employee churn across both regions was 21.2%, compared to predictions of 39%. These predictions were based on survey respondents who said they were "extremely likely" to change jobs in 2022. Turnover rates across both regions are levelling out following the pandemic. The predicted industry employee churn for 2023 is 18.6%.

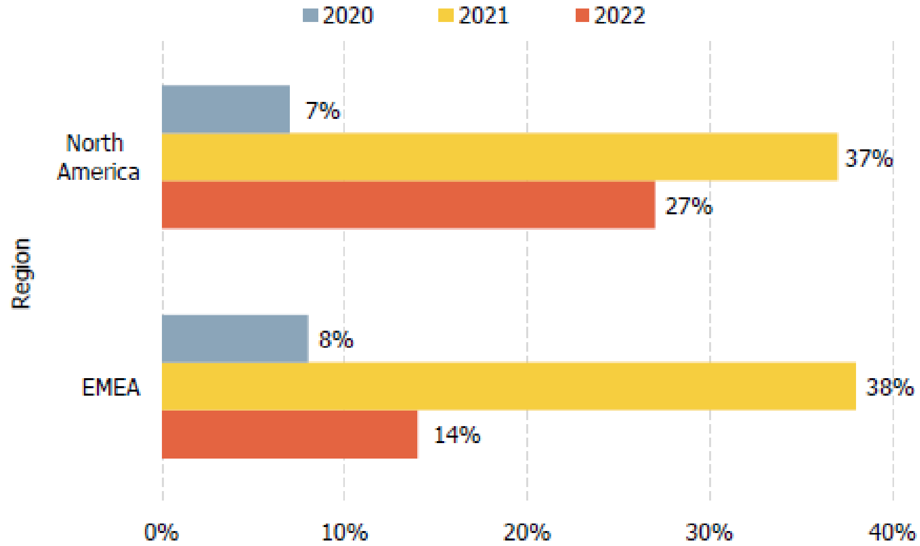


Fig. 281. Industry employee churn by year in the U.S. and EMEA; source: Alexander Daniels Global

Further ADG studies show professionals increasingly believe salaries in the AM industry are competitive compared with similar industries. The studies show that 32% of professionals believe AM salaries are "competitive" or "highly competitive." This contrasts with only 25% of professionals who thought the same way in 2021.

In recent years, global AM salary increases year-over-year have been marginal. In 2022, AM salaries in the U.S. increased by 12.6%. This is compared to a 7.7% increase in the Asia-Pacific (APAC) region and a 2.5% decrease in the EMEA region. Overall, salaries continue to grow across the AM industry. EMEA may be experiencing a drop in salaries in response to salary hikes seen in 2021.

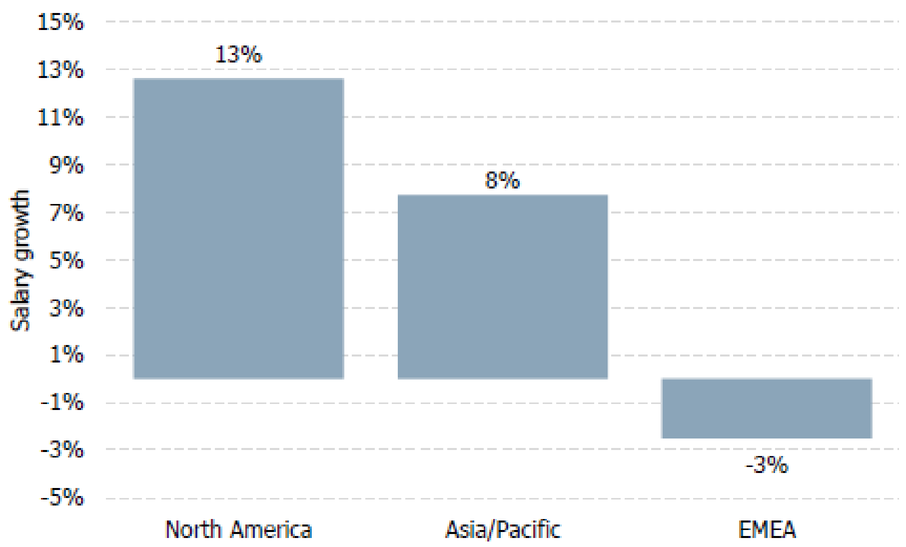


Fig. 282. AM salary growth by region in 2022; source: Alexander Daniels Global

While the talent market has seen healthy growth, hiring conditions may become less favorable for talent in 2023. Due to industry layoffs in 2022, employee turnover in 2023 is expected to be greater than previously predicted. A better fit will likely be sought by professionals and companies. Employers may find it easier to attract and engage professionals with requisite experience resulting from new talent entering the market and anticipated turnover.

Sustainability and a circular economy

by Steffen Schmidt

Change is needed if the world is to reach net-zero emissions by 2050 and meet the 1.5°C (2.7°F) limit set by the Paris agreement. To date, efforts to tackle the climate crisis have focused on a transition to renewable energy, complemented by improved energy efficiency. According to the Ellen MacArthur Foundation, these measures can only address 55% of the required emissions reduction. Meeting climate targets will require tackling the remaining 45% associated with manufacturing.

The Ellen MacArthur Foundation paper, titled *Completing the Picture*, further discusses the impact of applying circular economy strategies to four key industrial materials (concrete, steel, plastic, and aluminum). The paper predicts such strategies could help achieve a 40% reduction in emissions by 2050. The Danish AM Hub has a mission to promote the use of AM with a focus on sustainability. From these sources and others, the following paragraphs summarize four interlinked steps toward a more sustainable use of AM.

A significant benefit of 3D printing is on-demand manufacturing, thus reducing the need for warehousing. Since AM does not rely on long lead time tooling, production can start once an order has been received. Products can be shipped to individual consumers soon after production, eliminating the need for storage. AM also supports a trend toward product variance and moving from central to more decentralized production. Danish eyewear manufacturer Monoqool has relocated production from Japan to Denmark. It began to manufacture eyeglasses by AM and only in smaller quantities based on demand. The change in strategy resulted in Monoqool being named one of the fastest-growing companies in Denmark in 2018.

Fig. 283. 3D-printed eyeglass frames produced on demand, courtesy of Monoqool

Material substitution is a significant part of the solution to reducing carbon emissions. It involves using renewable, low-carbon, or secondary and waste materials as alternatives for production. These materials provide the same function but produce less emissions than conventional feedstock. The use of AM with recycled waste materials is developing rapidly. Signify N.V. (formerly known as Philips Lighting) is taking advantage of these opportunities. Signify converts old CDs and fishing nets into filament and 3D prints new lamps with this material. The company is planning to use more waste materials in the future.

Fig. 284. Bespoke lamps produced from old fishing nets and CDs, courtesy of Signify

Far too many products are designed to be disposable. AM can contribute to enhancing resource efficiency and the creation of products with longer lifespans. AM facilitates the creation of complex geometric shapes and features, which can lead to a reduction in material, part consolidation, simplified assembly lines, and improved product functionality. Also, AM makes it possible to optimize part design toward easier maintenance, repair, and restoration, thus reducing the need for replacement parts. Product disposal can be delayed by increasing customer attachment to a product, and personalization options made possible with AM can help.

3D printing does not always have a completely positive impact on sustainability. The initial energy consumption of the AM process and the increased carbon footprint of 3D printer feedstock can have a negative impact. However, this can be offset by weight reduction, leading to lower energy consumption over the life of a product. The full impact of AM on sustainability and the circular economy is best understood by considering a product's entire life cycle. AM can help support sustainability throughout a product's life, including raw materials, manufacturing, packaging, distribution, operation, and disposal.

Landscape of AM startups

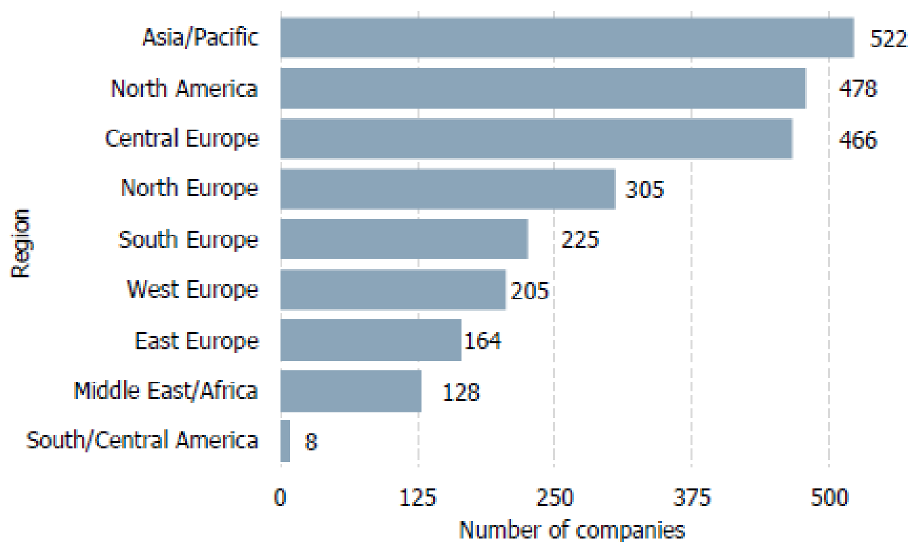
by Alexander Schmoeckel

AM Ventures (AMV) is a globally active venture capital fund focusing on early-stage startups developing hardware, software, materials, and applications for industrial AM. The company analyzes business plans, tracks funding rounds, and monitors the survival and success rates of

AM companies. The information gathered from AMV's work gives insight into the investment environment, trends, and characteristics among successful startups.

AMV focuses on companies developing and implementing industrial products and services. Of the 2,501 companies scouted so far, 338 were identified in 2022. Regions showing the highest numbers of AM startups are APAC, Central Europe (Germany, Austria, and Switzerland), and North America. The following chart shows the number of AM startups scouted by region since AMV's inception in 2015.

Fig. 285. Cumulative number of AM startups by region ; source: AM Ventures



Certain regions are fertile breeding grounds for young companies. In the U.S., Austin, Texas, Boston, Massachusetts, Denver, Colorado, and Silicon Valley, California have a strong focus on hardware, software and materials. In Europe, the metropolitan areas of Munich, Germany, Vienna, Austria, and Zurich, Switzerland are the top three regions. Each specializes in its own area of technology. Within APAC countries, Singapore and Seoul, South Korea are identified as highly innovative regions. Another regional AM powerhouse showing high numbers of startups is Tel Aviv, Israel. All 10 regions have the following four main success factors in common:

- World-class technical universities, providing highly educated talent
- Availability of large corporations with high-tech capabilities, serving as partners and customers
- Experienced and well-connected angel and other investors, providing funds and relevant networks for fast-growing entrepreneurial AM companies
- Outstanding technical and commercial infrastructure with worldwide access

In 2022, for the first time, more than half of the companies identified were focused on applications, as shown in the following chart. This segment grew from 47% in 2021 to 52% in 2022.

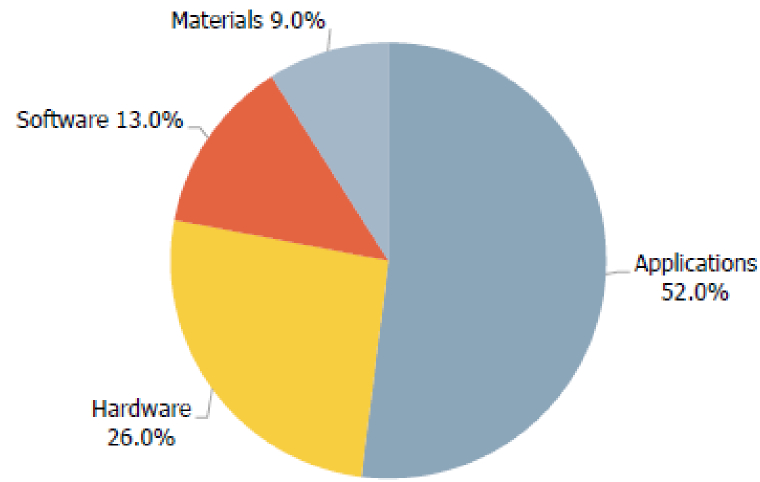


Fig. 286. Startups by sector; source: AM Ventures

The growth in application startups is a promising indication that AM is gaining further traction as a production method for end-use applications. It is expected that young companies will continue to present new approaches to improving reliability and ease of use of AM.

Despite 2022 stock price drops for publicly listed AM companies, investment funding has been largely unaffected. The same year, funding for AM increased strongly and reached an all-time high of more than $2.1 billion. This figure excludes special purpose acquisition company (SPAC) mergers and initial public offerings (IPO)s. The average annual growth rate for startup investments has been 62% since 2013. Major funding events in 2022 in the hardware, software, materials, and applications sector include the following:

- Scrona raised $6.7 million in Series A funding to develop ultra-high-resolution 3D printing
- Headmade Materials, inventor of a cold metal fusion 3D printing process, raised $2.5 million in Series A funding
- Fortius Metals raised $2 million in seed funding to scale production capacity of wire alloys for large-format metal 3D printing
- Seurat Technologies raised $21 million to commercialize its patented Area Printing technology
- 9T Labs raised $17 million in Series A funding to commercialize its carbon-fiber 3D printing technology
- Redefine Meat raised $135 million to expand production of 3D-printed meat replacement
- Divergent Technologies raised $160 million Series C funding, followed by a $100 million investment by Hexagon, to industrialize its integrated platform to 3D print high-performance cars
- Fictiv raised $100 million in Series E funding to market its on-demand 3D printing technology

– VulcanForms raised $355 million to expand and operate its digital manufacturing infrastructure
– Boston Micro Fabrication raised $43 million in Series C funding to develop its microscale 3D printing systems
– Synera (previously ELISE), provider of a connected engineering platform, raised $14.8 million in Series A funding to expand its business reach
– MolyWorks subsidiary Continuum raised $36 million to scale production of its sustainable metal powders

Merger and acquisition activities continued throughout 2022 and into 2023. Further consolidation of the AM market is expected.

Startups and early-stage investments

Startup companies and early-stage investments are a dynamic part of the developing AM ecosystem. The following table records 90 investment transactions involving startup and developing technology companies related to AM recorded between January 1, 2022 and February 28, 2023. This table does not include investments made "under the radar" in which startups and investors do not disclose the transactions. The figures in the "Amount" column are millions of dollars.

Date	Company	Country	Amount	Round	Lead investor	Focus
22-Jan	Adaxis	France	$1.10	Pre-seed	EIT Manufacturing	software
22-Jan	Seurat	U.S.	$21.00	Series B	Xerox Ventures	systems
22-Jan	Equispheres	Canada	$3.50	Grant	FEDDEV	materials
22-Jan	Redefine Meat	Israel	$135.00	Not specified	Hanaco Ventures	systems
22-Jan	Headmade Materials	Germany	$6.30	Not specified	EIC Accelerator	materials
22-Jan	Healshape	France	$7.40	Series A	Pulsalys SAS	materials
22-Feb	Elementum 3D	U.S.	$22.00	Series B	Not specified	materials
22-Feb	HBD	China	$60.00	Series A	Qianhai FOF	systems
22-Feb	Nuclera	UK	$42.50	Series B	M&G, Amadeus Capital Partners	systems
22-Feb	DyeMansion	Germany	$16.40	Not specified	EIC, European Investment Bank	systems
22-Feb	Q5D	UK	$2.50	Seed	Chrysalix Venture Capital	systems
22-Feb	Headmade Materials	Germany	$2.70	Series A	AM Ventures	materials
22-Feb	Stereotech	Russia	-	Not specified	VEB Ventures	systems
22-Feb	Scrona	Switzerland	$9.60	Series A	AM Ventures	systems
22-Feb	ICON	U.S.	$185.00	Series B	Tiger Global Management	systems

Date	Company	Country	Amount	Round	Lead investor	Focus
22-Feb	Raise3D	China	$14.60	Series C	Shanghai Jinpu	systems
22-Feb	9T Labs	Switzerland	$17.00	Series A	Stratasys, Solvay	systems
22-Mar	Black Buffalo 3D	U.S.	$3.50	Seed	Not specified	systems
22-Mar	Diamond Age	U.S.	$50.00	Series A	Prime Movers Lab	systems
22-Mar	Plantish	Israel	$12.50	Seed	State Of Mind Ventures	systems
22-Apr	Andiamo	U.S.	$0.50	Seed	ERA	services
22-Apr	Mosaic Manufacturing	Canada	-	Seed	Techstars	systems
22-Apr	Restor3D	U.S.	$23.00	Not specified	Not specified	services
22-Apr	Lazarus 3D	U.S.	$6.00	Seed	Ecliptic Capital	services
22-Apr	Divergent	U.S.	$160.00	Series C	Not specified	systems
22-Apr	X-Bow Systems	U.S.	$27.00	Series A	Crosslink Capital	services
22-May	Mooji Meats	U.S.	$3.00	Seed	Y Combinator	systems
22-May	COBOD	Denmark	-	Not specified	GE Renewable Energy	systems
22-May	Fictiv	U.S.	$100.00	Series E	Activate Capital	services
22-May	MakerBot & Ultimaker	U.S.	$62.40	Not specified	NPM Capital, Stratasys	systems
22-May	6K	U.S.	$102.00	Series D	Koch Strategic Platforms	materials
22-May	KLOwen	U.S.	$10.50	Series A	Columbia Pacific Advisors	systems
22-May	Launcher	U.S.	$1.70	Grant	U.S. Space Force	services
22-Jun	Reaction Dynamics	Canada	$3.50	Grant	Ngen	services
22-Jun	Inventia	Australia	$3.00	Not specified	HESTA	systems
22-Jun	Kings 3D (Jinshi)	China	-	Series C	Morgan Stanley	systems
22-Jun	Ai Build	UK	$3.20	Not specified	ACT Venture Partners	systems
22-Jun	Cocuus	Spain	$2.70	Pre Series A	Big Idea Ventures	materials
22-Jun	Triditive	Spain	$5.50	Not specified	Not specified	systems
22-Jun	Latitude	France	$10.90	Series A	Crédit Mutuel Innovation	services
22-Jun	Synteris	U.S.	$2.70	Grant	ARPA-E	materials
22-Jun	Ampcera	U.S.	$1.50	Grant	U.S. Department of Energy	services
22-Jul	VulcanForms	U.S.	$355.00	Not specified	Eclipse Ventures	systems
22-Jul	Chenglian Technology	China	$20.40	Series A	Zhencheng Capital	systems

Date	Company	Country	Amount	Round	Lead investor	Focus
22-Nov	Rosotics	U.S.	$0.80	Pre-seed	Draper Associates	systems
22-Nov	ICON	U.S.	$57.20	Grant	SBIR Phase III	systems
22-Dec	Fortius Metals	U.S.	$2.00	Seed	AM Ventures	materials
22-Dec	Additive Assurance	U.S.	$4.10	Not specified	Significant Capital Ventures	software
22-Dec	Fortify	U.S.	-	Late Stage VC	Lockheed Martin Ventures	systems
22-Dec	Continuum	U.S.	$36.00	Not specified	Ara Partners	materials
22-Dec	Syenta	Australia	$2.50	Seed	Blackbird	systems
22-Dec	Qbeam	China	$14.60	Series A	Not specified	systems
23-Jan	Steakholder Foods	Israel	$1.00	Grant	SIIRDF	services
23-Jan	ThinkMetal	India	$0.20	Pre-seed	100X.VC	services
23-Jan	Mycorena/ Revo Foods	Sweden	$1.60	Grant	Vinnova, Eurostars	materials
23-Feb	TraBTech	Turkey	$6.00	Not specified	Not specified	services
23-Feb	Dimension Inx	U.S.	$12.00	Series A	Prime Movers Lab	services
23-Feb	Freeform	U.S.	$41.00	Series A	Founders Fund	services
23-Feb	Fabric8Labs	U.S.	$50.00	Series B	NEA	systems
23-Feb	Largix	Israel	$1.00	Not specified	OJSC	systems
23-Feb	Xolo	Germany	$8.70	Series A	Not specified	services
23-Feb	Zellerfeld Shoe	U.S.	$15.00	Seed	Founders Fund	services

The reported numbers in the table are predominantly investments in equity. Government grants to commercial entities were also included in the previous table. Grants to non-commercial entities, such as research or academic institutions, were excluded. Investments or grants less than $100,000 were also excluded.

Sources of funding for companies in the table are public and private investment companies (e.g., venture capital firms, government investment agencies, and individuals). Funding also comes from corporations taking a position in a startup company, either directly or through a corporate venture arm established for making early-stage investments.

Recipients of the funding in the previous table were involved in an AM-related development or commercial activity—a requirement to be included. These developments and activities involve AM systems, materials, software, and services. In some cases, companies whose activities do not directly involve AM were included, but only if their products or services rely primarily on AM. Internal investments by developed companies in new plants and activities were excluded.

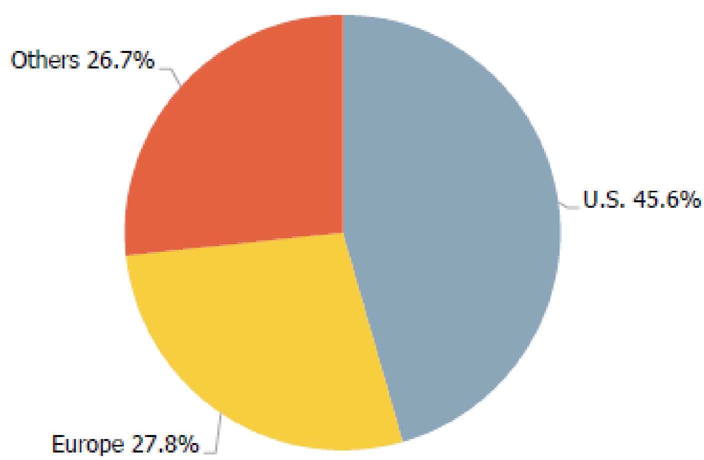
In some cases, investments or acquisitions were announced, but details, such as the amount of financing, the name of the round, or the investor's identity were omitted. Of the 90 investment transactions recorded, 77 (86%) reported the investment amount, or the amounts were obtained from regulatory filings.

The reported investments range from $200,000 to $355 million. Among companies reporting the investment amount, the average investment or value of the transaction in 2022 was $28.4 million, an increase from the $24.4 million reported in 2021. The median investment was $8.7 million, down from $13 million reported in 2021.

In the reporting period, total investment in AM startups was $2.25 billion. This amount excludes investments not reported or investments listed without transaction amounts. Investments made in countries that do not report venture investments as frequently as in the U.S. and Europe were excluded from this estimate. In the 12-month period from March 1, 2022 to February 28, 2023, the total investment amount was about $1.7 billion. In the calendar year 2022, the amount invested was about $2.1 billion.

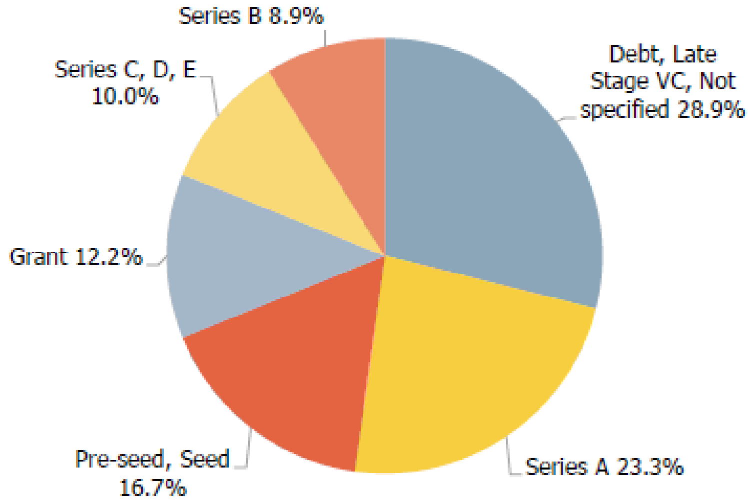
Companies based in the U.S. accounted for 45.5% of the reported transactions, as shown in the following chart. European companies reported 27.7% of the transactions. All other countries reported 26.7% of the transactions. The culture of investment and reporting differs by region and is likely to be a cause for lack of information on startup activity in some parts of the world.

Fig. 287. Investments into startups by region; source: Wohlers Associates



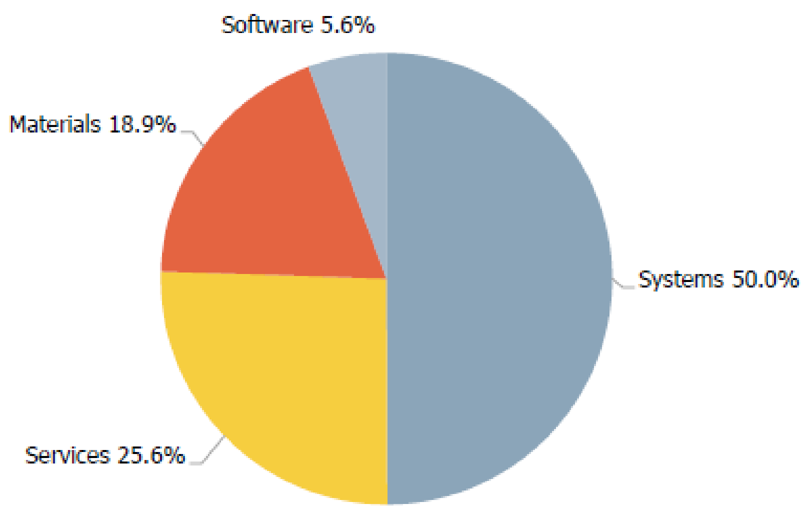
Regarding the reported stage of investment, 23.3% were Series A investments, 16.7% were pre-seed or seed investments, and 10.0% were Series C, D, or E investments. 8.9% were Series B. Grants accounted for 12.2% of the reported transactions. The remaining 28.9% were debt and venture capital financed, accounting for two transactions, or the company did not report the stage of investment.

Fig. 288. Investments into startups by investment stage; source: Wohlers Associates



Investments in AM system developers accounted for 50.0% of the transactions, while material developers accounted for 18.9%. Many systems developers also develop materials for use on their systems. Companies providing services, including manufacturing, accounted for 25.6%. Investments in software companies represented only 5.6% of the reported transactions.

Fig. 289. Investments into startups by sector; source: Wohlers Associates



New AM companies

New AM companies are developing novel approaches to solve old and new problems. These companies are working to develop systems, software, materials, and services for AM. This section includes a list of 103 companies focused on developing systems, materials, and software that will likely play a role in shaping the future of AM. These companies are in different stages of development. Depending on the technology and application, commercial offerings might take years to reach the market. Some may never reach commercialization, while others might be eclipsed by competing technologies. Others are likely to be acquired by larger companies.

Several interesting projects made progress this past year. Seurat, a Boston-area company, revealed further details on its Area Printing technology. The process being commercialized originated at Lawrence Livermore National Laboratory. The company claims its metal AM process is 10 times faster than current laser PBF processes. Seurat believes it could achieve speeds 100 times faster than current metal AM systems within two or three years. Area Printing is a laser-based technology powered by renewable energy. The company has raised $79 million in venture financing from nine venture capital funds, most recently completing a $62 million round in January 2022.

Another Boston area metal AM company made headlines in 2022. VulcanForms raised $355 million in funding to develop its laser PBF process. The company said its system will deliver 100 kilowatts of laser power, which is considerably more than competing laser PBF systems on the market. The company will operate two manufacturing facilities in Massachusetts, one of which will be equipped with two megawatts of capacity. The company plans to offer AM only as a service.

Fabric8Labs announced in early 2023 a funding round of $50 million to develop an electrochemical AM process. The company began in 2015 but kept a low profile until recently. The company said the process operates at room temperature to build complex metal parts at an atomic level from a water-based feedstock containing dissolved metal ions. Little more is known about the process, which is focused on small parts.

AC company Diamond Age gained notice when it raised $50 million in funding to develop a 3D-printed construction platform. Black Buffalo 3D also made progress in AC, raising a small seed round of investment in 2022. These companies join more established AC companies ICON and COBOD, which raised about $200 million in funding between them. COBOD collaborated with GE Renewable Energy and received corporate investment from CEMEX, a cement company.

Use of AM for medical applications is well established, yet new companies are finding their way into the market. Restor3D was founded in 2017, with 2022 being a breakout year for the company. It raised $23 million in April 2022. The company has developed a range of personalized medical devices produced by AM. French company Lattice Medical has developed a 3D-bioprinted material for use in breast reconstruction. The company raised €8 million in October 2022.

The companies in the following table are developing a wide range of AM technologies, systems, and applications. Some of them have been actively developing technologies and products for years, while others recently announced plans or emerged from stealth mode development. None of the companies in the table are offering commercially available products, as of March 2023.

Company	Country	Website
1A Technologies	Germany	www.1a-technologies.com
3D Hybrid Solutions	U.S.	www.3dhybridsolutions.com
3DEO	U.S.	www.3deo.co
3Deus Dynamics	France	www.3deusdynamics.com
3D-Figo GmbH	Germany	www.3d-figo.de/en/about-us
3DKG	Italy	www.3dkg.eu/en/granulab.html
9Tlabs	Switzerland	www.9tlabs.com
Additive Alliance	U.S.	www.additivealliancellc.com
additive electronics	Germany	www.additive-electronics.com
Additive Solutions (AddSol)	Russia	www.addsol.ru
Aerosint	Belgium	www.aerosint.com
AFPT	Germany	global.afpt.de
Amaero	Australia	www.amaero.com.au
Ambots	U.S.	www.ambots.net
Arevo Labs	U.S.	www.arevo.com
Atlant 3D Nanosystems	Denmark	www.atlant3d.com
ATMAT	Poland	www.atmat.pl
Axtra3D (SP/SM)	U.S.	www.axtra3d.com
Beeverycreative	Portugal	www.beeverycreative.com
Big Metal Additive	U.S.	www.bigmetaladditive.com
BotFactory	U.S.	www.botfactory.co
Canon	Japan	www.canon.com
Caracol	Italy	caracol-am.com
CleanGreen3D	Ireland	cleangreen3d.com
Compound Dynamics	U.S.	www.compounddynamics.com
Continuous Composites	U.S.	www.continuouscomposites.com
Coriolis	France	www.coriolis-composites.com
Creative 3D Technologies	U.S.	www.creative3dtechnologies.com
Daegun	South Korea	www.daeguntech.co.kr
Digital Alloys	U.S.	www.digitalalloys.com
DM3D	U.S.	www.dm3dtech.com
DN Solutions	South Korea	www.dn-solutions.com/en/main/index.do
Electroimpact	U.S.	www.electroimpact.com
Evobeam	Germany	www.evobeam.com
Exaddon	Switzerland	www.exaddon.com
Fabmaker	Germany	www.fabmaker.com
Femtoprint	Switzerland	www.femtoprint.ch
Forust (Desktop Metal)	U.S.	www.forust.com
Foundry Lab	New Zealand	www.foundrylab.com
Freeform Composites	Australia	www.freeformcomposites.com

Company	Country	Website
Freemelt	Sweden	www.freemelt.com
Grante Corp.	Hungary	www.duplex3d.com
Grid Logic	U.S.	www.grid-logic.com
Haute Fabrication	U.S.	www.hautefabrication.com
Hermle	Germany	www.hermle-generative-manufacturing.com
Holo	U.S.	www.holoam.com
Huvitz	South Korea	www.huvitz.com
Ibarmia	Spain	www.ibarmia.com/en
ICON	U.S.	www.iconbuild.com
Imprinta	Russia	www.imprinta.ru
Incremental3D	Austria	www.incremental3d.eu
Inkbit	U.S.	www.inkbit3d.com
Innovatica	Poland	www.innovatica.com.pl
Klema	Poland	www.klema.eu
Kloe	France	www.kloe-france.com
Kwambio - service	U.S.	www.kwambio.com
Largix	Israel	www.largix.com
Lasers and Apparatus	Russia	www.laserapr.ru
Lincoln Electric	U.S.	www.additive.lincolnelectric.com
Magnus Metal	Israel	www.magnusmetal.com
Mantis Composites	U.S.	www.mantiscomposites.com/index.html
Mantle	U.S.	www.mantle3d.com
Maxrotec	South Korea	www.maxrotec.com
Mazak	Japan	www.mazak.co.jp
Meld Manufacturing	U.S.	www.meldmanufacturing.com
MetalWorm	Turkey	www.metalworm.com
Microlay	Spain	www.microlay.com
Mitsubishi Electric	Japan	www.mitsubishielectric.com
Mitsubishi Heavy Industries	Japan	www.mhi.com
Mogassam	Egypt	www.mogassam.com
Moi	Italy	www.moi.am
Norsk Titanium	Norway	www.norsktitanium.com
Notion Systems	Germany	www.notion-systems.com
NPPower	Slovenia	www.nppower.eu
OVE	Poland	www.o-v-e.com
PolarOnyx	U.S.	www.polaronyx.com
ponticon	Germany	www.ponticon.de
Pro-Beam Systems	Germany	www.pro-beam.com/en
Procada	Sweden	www.procada.se

Company	Country	Website
Q.Big 3D	Germany	www.qbig3d.de/en
R3 Printing	U.S.	www.r3printing.com
Rapid Liquid Print	U.S.	www.rapidliquidprint.co
RAPLAS	UK	www.raplas.com
Ray	South Korea	www.raymedical.com
Redefine Meat	Israel	www.redefinemeat.com
Ricoh	Japan	www.ricoh.com
Russian 3D Printers (3DSLA.RU)	Russia	www.3dsla.ru
Samyoung	South Korea	www.sym.co.kr
SavorEat	Israel	www.savor-eat.com
Seurat Technologies	U.S.	www.seuratech.com
Solo Additive	China	www.solo-additive.com
Steakholder Foods	Israel	www.steakholderfoods.com
Sun Metalon	Japan	sunmetalon.com
Trio Labs	U.S.	www.trio-labs.com
TSC	China	www.tsc-bj.com
ValCUN	Belgium	www.valcun.be
Voltera	Canada	www.voltera.io
VRC Metal Systems	U.S.	www.vrcmetalsystems.com
VulcanForms	U.S.	www.vulcanforms.com
Weber	Germany	www.hansweber.de/en
Weisser	Germany	www.weisser-web.com
Xerion Berlin Laboratories	Germany	www.xerion.de
Xolo	Germany	www.xolo3d.com

The future of AM

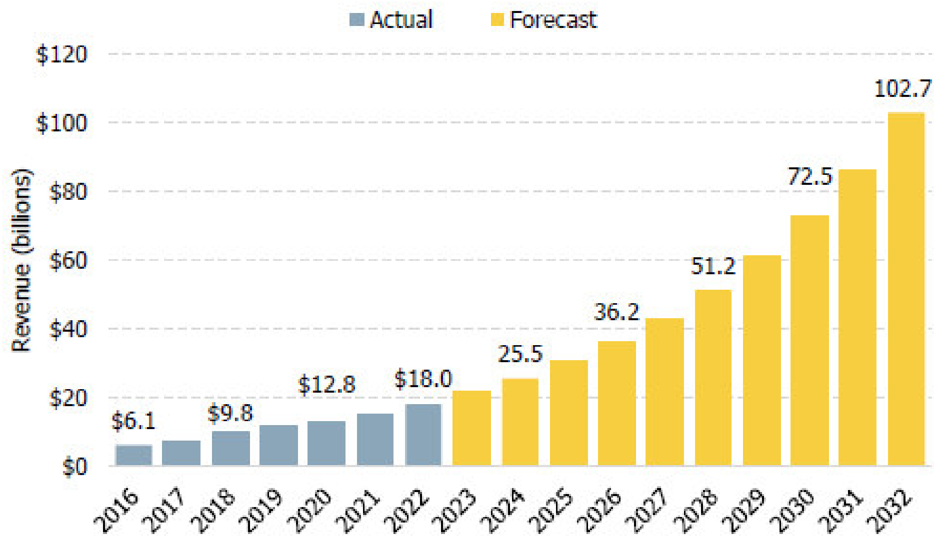
Many in product development and manufacturing are interested in gaining insight into the future of AM. They want to anticipate how the technology and its application will further develop as they consider their adoption and investment strategies. No one knows the future with 100% certainty, but Wohlers Associates has decades of information and data that it uses to better anticipate what is ahead. Simply extending growth trend lines is a good place to start.

Market forecast

It is important to consider a range of factors when anticipating the future development of AM. They include the health of the economy worldwide, expected adoption plans by industrial sectors, and new and potential "game-changing" developments in machines, materials, software, and applications. Other factors are pandemics, natural disasters, and wars, but they are difficult to gauge and foresee.

The following graph shows the historical growth through 2022 based on hard data received from hundreds of companies worldwide. It also includes the future growth that Wohlers Associates expects in the coming years. The AM industry is expected to exceed $100 billion for the first time in 2032.

Fig. 290. Market forecast; source: Wohlers Associates



Growth drivers

Most investors and organizations adopting AM are interested in knowing what will lead to the figures shown in the right half of the previous graph. AM will become a more common method of end-use part production, which will contribute to this growth. For this to occur, systems will become much faster, which will reduce the production cost per part. Build time is a large contributor to part cost, so doubling the speed of a machine is almost like getting two parts for the price of one. Vitro3D, a startup in Boulder, Colorado, claims its volumetric printing approach is about 100 times faster than other VPP systems. It is this kind of speed improvement that will "move the needle" in the adoption of AM.

If Vitro3D and other companies can deliver on their promises, the AM industry could benefit from the game-changing solutions it has been seeking. It certainly changes the equation when determining whether AM is a fit for a production application. Breakeven points will improve from hundreds or thousands of parts to tens, even hundreds of thousands.

To put this into perspective, suppose the total production volume of a car is 450,000 units. The car manufacturers are trying to determine whether to use AM or injection molding for producing a polymer part used in each car. If the AM breakeven point for the part exceeds 450,000, it will be more economical to use AM than injection molding. Using AM can unlock additional features such as automatic serialized part numbers, custom textures, and a lower carbon footprint.

Determining breakeven points will continue on a case-by-case basis, with part size, material, and complexity being major factors.

Companies such as Relativity are driving interest in the rocket launch and space industry. The company claims that 85% of its Terran 1 launch vehicle was produced by its proprietary directed energy deposition (DED) system. Some parts, such as those for the engine, were produced by PBF. The work at Relativity is bringing a great deal of attention and excitement to thousands of other space-related companies. More than 5,000 of these companies are in the U.S.

The use of AM for custom, personalized, one-off, and limited-edition products is expanding. We are seeing an impressive range of parts and products made for footwear, eyewear, jewelry, and other consumer products. Add to this the wide range of custom jigs, fixtures, guides, gauges, and other types of factory tooling that countless companies are producing routinely.

For more than a decade, the AM industry has expected the automotive industry to adopt AM more widely for series production applications. Costs are simply too high for mainstream cars and trucks. One company, Divergent, is working hard to change this. Already, the company is 3D printing and shipping a 30-kg (66-lb) aluminum chassis to Aston Martin. Meanwhile, the company is working on more than 20 additional automotive platforms.

A big part of the business model at Divergent is reducing product development time from three years to three months. Divergent said it is reducing mass by 40% and part count by 80%. Building relatively large and intricate automobile structures by metal AM is usually cost-prohibitive, even for manufacturers such as Aston Martin. AM has long been used to create series parts for high-end automobiles produced in relatively small quantities, but nearly all of them have been polymer, which is easier to justify.

The work at Divergent could serve as a stepping stone toward wider-spread adoption among auto manufacturers. The significant wave of new electric vehicles, designed from the ground up, offers an interesting opportunity for the AM industry. A reduction in weight largely factors into the calculation.

Additional growth will be driven by a range of industrial sectors, including aerospace, healthcare, military, and drones for a wide range of applications, coupled with innovative business models and sustainability. Machines that produce large parts and structures, particularly DED systems, are gaining traction and likely to contribute to industry-wide growth over the next several years. The idea of replacing inventories with a digital version, combined with on-demand manufacturing, has great potential, but adoption thus far has been weak.

Obstacles

Several obstacles have and will continue to impact the growth of AM. The cost of industrial machines and materials remains significant because both are still relatively expensive. Materials especially affect manufacturing costs as part volumes increase. In low quantities, material cost is much less of a factor.

The post-processing of parts, and the labor associated with it, can typically represent up to 30% of the total cost of an AM part. In some cases, especially with metal parts, it can represent even more. Automation can help, but upfront costs can also be expensive, especially when manufacturing volumes are low. Fortunately, organizations are finally recognizing and addressing the cost associated with post-processing. Five years ago, most were not.

DfAM is an expense that the inexperienced often overlook. Neglecting it can make it impossible to build a strong business case in favor of using AM. An example of DfAM is consolidating multiple parts into one, thus eliminating manufacturing processes, inventory, assembly, maintenance, and certification paperwork. Methods of DfAM can improve product performance and reduce material and weight, sometimes significantly.

Most AM processes produce anisotropic parts. This means the strength, elastic, and fatigue properties are not equal in all directions. For some processes, such as MEX, the x and y directions are usually stronger than the z direction. This limitation can be problematic when trying to optimize the build orientation of an AM part in a machine. The limited number of materials available for AM, compared to conventional manufacturing, is another consideration for designers and engineers.

AM systems are not always produced to the same manufacturing quality standards as conventional manufacturing equipment, such as computer numerical control (CNC) machines. A customer may purchase multiple machines of the same model, yet the customer will often find differences between these machines. This impacts repeatability and part quality, which is unacceptable in the world of manufacturing. The problem has improved some, but it remains after more than 30 years of producing machines for AM.

Qualification and certification processes associated with AM are a consideration and viewed as hurdles by many. An aerospace company that Wohlers Associates met with in 2022 said it could design and manufacture complex parts in 4–6 weeks, but it took substantially longer than this for the qualification process.

The use of AM for construction applications, such as buildings, bridges, park accessories, and other outdoor structures, is developing. The construction industry is discovering the strengths and limitations of additive construction (AC) and is trying to determine where it fits and when business cases are justified. AC will contribute some to the $102.7 billion AM industry forecast, but it will be limited by 2032, given the regulatory hurdles and what has been completed to date. The construction industry has long-established materials and processes and a large workforce, and all are ripe for change, but it will come slowly. In 20 years, AC could become sizeable.

Possible surprises in the future

It is easy to predict the future, but difficult to do it accurately. The 3D printing of food, personalized medicine, and electronics may not become mainstream by 2032, but these applications could gain traction by then. Several companies are in the early stages of printing food products, both from plants and living cells from animals. A handful of companies are testing the printing of medicine, but only one (Aprecia) has commercialized a product. The printing of efficient circuit boards may be further into the future, but using AM to make sensors, antennas, and other electronic-related devices is currently underway.

Helmets are used for American football, ice hockey, biking, skiing, the military, and a range of other uses. Products that reduce head injuries could help tens of millions around the world. Bauer Hockey, Carbon, EOS, the National Football League, National Hockey League, Riddell, and others are working on this application. 3D scanning an athlete's head can now be done with a phone. This data can be used to produce a custom liner optimized to absorb the shock during a hit or fall. It is difficult to know when this will become mainstream, but it will likely occur with time and investment.

Governments with strong branches of the military have incredibly large budgets. One or more may help underwrite much of the cost of developing end-to-end processes for custom helmet design. It would not stop there, however. Consider the opportunity of developing perfect-fitting backpacks, goggles and other optical devices, boots, and a wide range of accessories. Much of it will start with the military.

Imagine a future of printing batteries, digitizing and printing large aircraft structures, the printing of explosives by the military, and high-speed volumetric printing. The possibilities are almost endless. The printing of spare parts for the human body may be the Holy Grail, in a metaphorical sense. If someone loses a finger, a new one is printed using living cells from the patient. If a heart valve is damaged, a patient-specific version is printed and implanted. As we age, body parts will be swapped out with new ones. Complete organs and limbs may be further into the future, but skin, bone, teeth, and cartilage are on the horizon.

Closing comments

Some of what we envision may not happen in our lifetime or at all. The building blocks, however, are in place for most of it to occur. It is largely a matter of ingenuity, funding, hard work, and determination.

AM has already changed our lives, whether we realize it or not. Consider that most consumer products, sporting goods, automobiles, and airplanes have benefited from AM at some point in their design and production lifecycle. For example, nearly 600 Boeing 737 MAX commercial jets were in service in mid-2022. The aircraft features the LEAP engine from GE Aerospace and Safran, which includes 3D-printed fuel nozzles, combustion liners, and heat exchangers. In the future, many more companies will bridge the gap between using AM for concept modeling and prototyping to custom and series production. This is when AM will become much bigger.

The team at Wohlers Associates has worked tirelessly over the past 28 years to deliver the most up-to-date and impactful insights. We hope you gained a lot from this report. As your journey with AM unfolds, we would like to hear from you. We are always looking for good use cases and examples to consider for the next edition. We sincerely appreciate your support and contribution to the AM industry.

SYSTEM MANUFACTURERS

Industrial additive manufacturing (AM) systems manufacturers are presented geographically on the following pages. Included are the most prominent companies from around the world with known commercial activity. The rapid expansion of new companies and systems makes the task of tracking them more involved.

A division between industrial and desktop manufacturers was established years ago when the first low-cost RepRap printers were commercialized. After careful consideration, Wohlers Associates chose a price of $5,000 as a dividing line between the two classes of system. That decision has served for many years.

The distinction between industrial and desktop machines has since blurred. Many material extrusion (MEX) systems that are much larger than but similar to desktop systems are priced well above $5,000. Meanwhile, many vat photopolymerization (VPP) systems are priced less than $5,000 and compete favorably with machines that are more expensive. Even so, this report adheres to the established convention.

Several manufacturers are developing new processes, but some of them were not commercially available at the time of publishing this report. Many are covered in the "New AM companies" section in Part 7. Some companies have proprietary processes and/or materials but do not sell machines. Instead, revenue comes from selling parts made with their technology.

The following are the abbreviations for the AM processes discussed in this section.

MEX = material extrusion	VPP = vat photopolymerization
MJT = material jetting	PBF = powder bed fusion
BJT = binder jetting	DED = directed energy deposition
SHL = sheet lamination	

Asia/Pacific

Many companies in the Asia/Pacific region develop and sell industrial AM systems. Japan was a pioneer in the development of AM in the 1980s. China has risen as a prominent producer of systems in recent years. Manufacturers of AM systems and their products are profiled on the following pages.

Aspect

Aspect has produced and sold polymer PBF systems for nearly three decades. The company is also a veteran service provider.

Aspect, Inc.
Tokyo, Japan
www.aspect.jpn.com

Fig. 291. Chemical- and heat-resistant duct, courtesy of Aspect

Model name PBF (polymer)	Build volume, mm (in)	Materials	~Base x 1,000
AM-E3 300C	300 x 300 x 420 (11.8 x 11.8 x 16.5)	PP, PA, glass-filled PA, glass-filled PA6, FPA, PBT, glass-filled PBT	¥66,000
AM-E3 550C	550 x 550 x 520 (21.7 x 21.7 x 20.5)	same as above	¥74,000
AM-E3 150-HT	135 x 135 x 200 (5.3 x 5.3 x 7.8)	PPS, glass-filled PPS, carbon-filled PPS, PFA, PP, PA, glass-filled PA, glass-filled PA6, FPA, PBT, glass-filled PBT	¥72,000
AM-E3 300-HT	300 x 300 x 440 (11.8 x 11.8 x 17.3)	PPS, glass-filled PPS, carbon-filled PPS, PFA, PP, PA, glass-filled PA, glass-filled PA6, FPA, PBT, glass-filled PBT, fire-retardant PA, fire-retardant PA6	¥80,000
AM-E3 550-HT	550 x 550 x 540 (21.7 x 21.7 x 21.3)	PPS, glass-filled PPS, carbon-filled PPS, PFA, PP, PA, glass-filled PA, glass-filled PA6, FPA, PBT, glass-filled PBT	¥88,000

Bright Laser Technologies

Bright Laser Technologies, also referred to as BLT, grew out of research conducted at Northwestern Polytechnical University in China. The company produces metal PBF and DED systems.

Xi'an Bright Laser Technologies Co., Ltd.
Xi'an, China
www.xa-blt.com

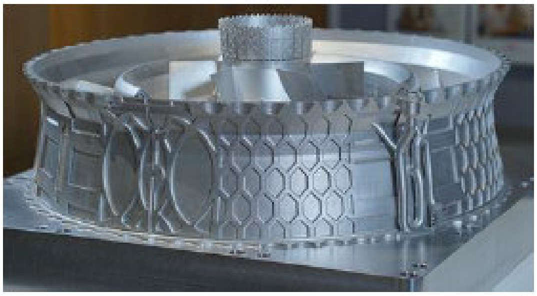


Fig. 292. Engine part manufactured on the BLT-S800 system, courtesy of BLT

Model name PBF (metal)	Build volume, mm (in)	Materials	~Base x 1,000
BLT-A160/A160D	160 x 160 x 100 (6.3 x 6.3 x 3.9)	titanium alloys, cobalt-chrome alloys	–
BLT-A300/A320	250 x 250 x 300 (5.9 x 5.9 x 7.9)	titanium alloys, aluminum alloys, stainless steel, tool steel, copper alloy, superalloys	–

BLT-A400	400 x 300 x 400 (15.7 x 11.8 x 15.7)	titanium alloys, aluminum alloys, stainless steel, tool steel, high-strength alloys, superalloys	–
BLT-A450	450 x 450 x 500 (17.7 x 17.7 x 19.7)	titanium alloys, aluminum alloys, stainless steel, tool steel, high-strength alloys, superalloys	–
BLT-S210	105 x 105 x 200 (4.1 x 4.1 x 7.9)	titanium alloys, aluminum alloys, stainless steel, tool steel, cobalt-chrome alloys, superalloys, copper alloy, tantalum alloys, tungsten alloy, magnesium alloy	–
BLT-S310/ S320	250 x 250 x 400 (9.8 x 9.8 x 15.7)	titanium alloys, aluminum alloys, stainless steel, tool steel, copper alloy, superalloys	–
BLT-S400	400 x 250 x 400 (15.7 x 9.8 x 15.7)	titanium alloys, aluminum alloys, stainless steel, tool steel, copper alloy, superalloys	–
BLT-S450	400 x 400 x 500 (15.7 x 15.7 x 19.7)	titanium alloys, aluminum alloys, stainless steel, tool steel, copper alloy, superalloys	–
BLT-S450T	400 x 450 x 500 (15.7 x 17.7 x 19.7)	titanium alloys, aluminum alloys, stainless steel, tool steel, copper alloy, superalloys	–
BLT-S450Q	450 x 450 x 500 (17.7 x 17.7 x 19.7)	titanium alloys, aluminum alloys, stainless steel, tool steel, copper alloy, superalloys	–
BLT-S510	500 x 500 x 1,000 (19.7 x 19.7 x 39.4)	titanium alloys, aluminum alloys, stainless steel, tool steel, copper alloy, superalloys	–
BLT-S515	400 x 400 x 1,500 (15.7 x 15.7 x 61)	titanium alloys, aluminum alloys, stainless steel, tool steel, copper alloy, superalloys	–
BLT-S600	600 x 600 x 600 (23.6 x 23.6 x 23.6)	titanium alloys, aluminum alloys, stainless steel, tool steel, copper alloy, superalloys	–
BLT-S800	800 x 800 x 600 (31.5 x 31.5 x 23.6)	titanium alloys, aluminum alloys, stainless steel, tool steel, superalloys	–
BLT-S1000	1200 x 600 x 1,500 (47.2 x 23.6 x 59)	titanium alloys, aluminum alloys, stainless steel, tool steel, superalloys	–
DED			
BLT-C400	600 x 600 x 1,000 (23.6 x 23.6 x 39.4)	titanium alloy, aluminum, high temperature alloy, Co-Cr alloy, stainless steel, high-strength steel, tool steel	–
BLT-C600	600 x 600 x 1,000 (23.6 x 23.6 x 39.4)	titanium alloys, high-strength and stainless steel	–
BLT-C1000	1500 x 1,000 x1,000 (59.1 x 39.4 x 39.4)	titanium alloys, high-strength and stainless steel, superalloys	–

Eplus3D

Eplus3D produces metal and polymer PBF and VPP systems for industrial applications.

Eplus3D Tech. Co, Ltd.
Hangzhou, China
www.eplus3d.com

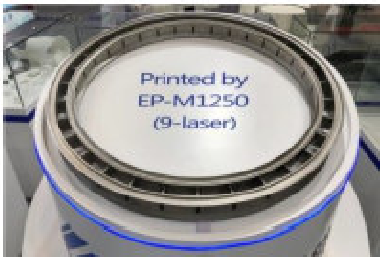


Fig. 293. Case printed on EP-M1250 (9-laser) system for an aerospace application, courtesy of Eplus3D

Model name	Build volume, mm (in)	Materials	~Base x 1,000
PBF (polymer)			
EP-C5050	500 x 500 x 500 (19.7 x 19.7 x 19.7)	PP, PE, TPU, TPE, PA, PS	$145
EP-C7250	720 x 720 x 500 (28.3 x 28.3 x 19.7)	PS, foundry sand	$200
EP-P380	380 x 380 x 500 (15 x 15 x 19.7)	PA11, PA12, glass-filled PA6, PP	$220
EP-P420	420 x 420 x 465 (16.5 x 16.5 x 18.3)	PA11, PA12, PA6, glass-filled PA6	$250
PBF (metal)			
EP-M150	150 dia. x 120 (5.9 dia. x 3.9)	same as above	$150
EP-M150Pro	153 dia. x 240 (6 dia. x 9.4)	same as above	$200
EP-M250Pro	262 x 262 x 350 (10.3 x 10.3 x 13.8)	same as above	$510
EP-M260	266 x 266 x 390 (10.5 x 10.5 x 15.4)	same as above	$450
EP-M300	305 x 305 x 450 (12 x 12 x 17.7)	same as above	$530
EP-M450	450 x 450 x 450 (17.7 x 17.7 x 17.7)	same as above	$700
EP-M450H	455 x 455 x 1,100 (17.9 x 17.9 x 43.3)	same as above	$1,000
EP-M650	650 x 650 x 800 (25.6 x 25.6 x 31.5)	same as above	$1,500
EP-M1250	1,258 x 1,258 x 1,350 (49.5 x 49.5 x 53.1)	same as above	$3,000
VPP			
EP-A450	450 x 450 x 400 (17.7 x 17.7 x 15.7)	same as above	$60
EP-A650	650 x 600 x 400 (25.6 x 23.6 x 15.7)	same as above	$80
EP-A800	800 x 800 x 450 (31.5 x 31.5 x 17.7)	same as above	$100

Farsoon

Farsoon was founded by industry veteran Xu Xiaoshu in 2009. The company's first metal AM machines became available in 2015.

Farsoon Technologies
Hunan, China
www.farsoon.com

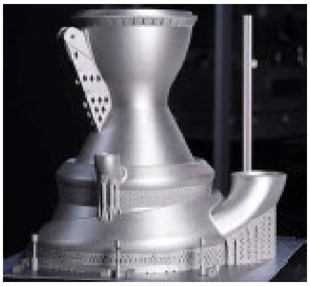


Fig. 294. Rocket engine combustion chamber printed on FS621M-4 in Inconel, courtesy of Farsoon

Model name	Build volume, mm (in)	Materials	~Base x 1,000
PBF (polymer)			
eForm	250 x 250 x 320 (9.8 x 9.8 x 12.6)	PA, fiber-, glass-, and mineral-reinforced PA, PP, elastomers	$120
252P series	250 x 250 x 320 (9.8 x 9.8 x 12.6)	PA, fiber-, glass-, and mineral-reinforced PA, PA6, PP, PPS, elastomers	$275
403P series	400 x 400 x 450 (15.7 x 15.7 x 17.7) 400 x 400 x 540 (15.7 x 15.7 x 21.3)	same as above	$300
Flight 403P	400 x 400 x 450 (15.7 x 15.7 x 17.7)	PA, glass-reinforced PA, elastomers	$350
	400 x 400 x 540 (15.7 x 15.7 x 21.3)	same as above	–
Flight 403P-2	400 x 400 x 450 (15.7 x 15.7 x 17.7) 400 x 400 x 540 (15.7 x 15.7 x 21.3)	same as above	–
HT1001P-2	1,000 x 500 x 450 (39.4 x 19.7 x 17.7)	PA, fiber-, glass-, and mineral-reinforced PA, PP, elastomers	$850
Flight HT1001P-4	1,000 x 500 x 450 (39.4 x 19.7 x 17.7)	PA, glass-reinforced PA, elastomers	$1,000
PBF (metal)			
FS121M	120 x 120 x 100 (4.7 x 4.7 x 3.9)	stainless steel, titanium	$120
FS200M-2	425 x 230 x 300 (16.7 x 9 x 11.8)	aluminum, maraging steel, stainless steel	–
FS273M	275 x 275 x 355 (10.8 x 10.8 x 14)	aluminum, bronze, Inconel, maraging steel, stainless steel, titanium	$320
FS273M-2	275 x 275 x 355 (10.8 x 10.8 x 14)	same as above	–
FS301M	305 x 305 x 410 (12.0 x 12.0 x 16.1)	aluminum, Inconel, stainless steel, titanium	$480
FS301M-2	305 x 305 x 410 (12.0 x 12.0 x 16.1)	same as above	–
FS422M-4	425 x 425 x 420 (16.7 x 16.7 x 16.5) 425 x 425 x 550 (16.7 x 16.7 x 21.7)	aluminum, bronze, Inconel, stainless steel, titanium	$950
FS621M-4	620 x 620 x 1,100 (24.4 x 24.4 x 43.3)	aluminum, Inconel, stainless steel, titanium	$1,600
FS621M Pro-6	620 x 808 x 1,200 (24.4 x 31.8 x 47.2)	same as above	$1,800
FS721M	720 x 420 x 420 (28.3 x 16.5 x 16.5)	aluminum, Inconel, maraging steel, stainless steel, titanium	$1,050

FS721M-4	720 x 420 x 420 (28.3 x 16.5 x 16.5)	same as above	_
FS721M-8	720 x 420 x 420 (28.3 x 16.5 x 16.5)	aluminum, Inconel, stainless steel, titanium	_

Mimaki

Mimaki was founded in 1975 as an inkjet printer manufacturer, which launched a full-color polymer MJT 3D printer in 2017.

Mimaki Engineering Co., Ltd.,
Nagano, Japan
www.mimaki.com

Fig. 295. Vacuum prototype printed with Mimaki's Pure Clear material, courtesy of Mimaki

Model name *MJT*	Build volume, mm (in)	Materials	~Base x 1,000
3DUJ-2207	203 x 203 x 76 (8 x 8 x 3)	photopolymer	$40
3DUJ-553	508 x 508 x 305 (20 x 20 x 12)	same as above	$180

UnionTech

UnionTech is a developer of industrial 3D printing solutions. Its products include equipment, materials, software, printing services, and cloud platforms.

Shanghai Union Technology Corp.
Shanghai, China
www.uniontech3d.com

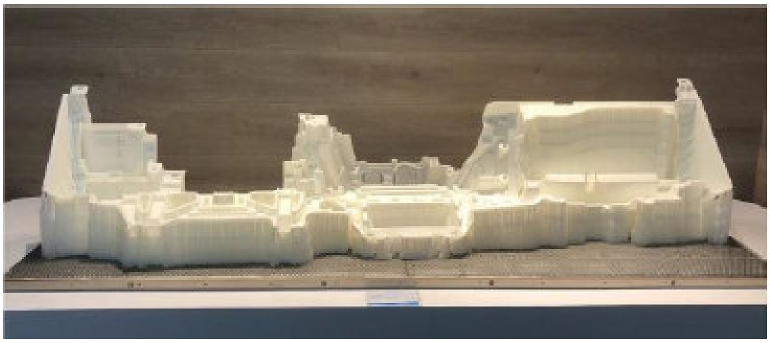


Fig. 296. Industrial accessories for an end-use application, courtesy of UnionTech

Model name *VPP*	Build volume, mm (in)	Materials	~Base x 1,000
RSPro600	600 x 600 x 500 (23.6 x 23.6 x 19.7)	photopolymer	–
RSPro800	800 x 800 x 500 (31.5 x 31.5 x 21.7)	same as above	–
RSPro1400	1,400 x 700 x 500 (55.1 x 27.6 x 19.7)	same as above	–
RSPro2100	2,100 x 700 x 800 (82.7 x 27.6 x 31.5)	same as above	–
Pilot250	250 x 250 x 250 (9.8 x 9.8 x 9.8)	same as above	–
Pilot450	450 x 450 x 450 (17.7 x 17.7 x 17.7)	same as above	–
Lite 800	800 x 800 x 550 (31.5 x 31.5 x 21.7)	same as above	–
Lite600	600 x 600 x 400 (23.6 x 23.6 x 15.7)	same as above	–
Lite450	450 x 450 x 350 (17.7 x 17.7 x 13.8)	same as above	–
G1400	1,400 x 700 x 500 (55.1 x 27.6 x 19.7)	same as above	–
G1800	1,800 x 900 x 600 (70.9 x 35.4 x 23.6)	same as above	–
G2100	2,100 x 700 x 800 (82.7 x 27.6 x 31.5)	same as above	–
D800	768 x 432 x 30 (30.2 x 17 x 1.2)	same as above	–
E140	144 x 81 x 80 (5.7 x 3.2 x 3.1)	same as above	–
S300+	250 x 140 x 240 (9.8 x 5.5 x 5.4)	same as above	–
S200	192 x 108 x 200 (7.6 x 4.2 x 7.9)	same as above	–

XYZprinting

XYZprinting, offers a wide range of AM systems. Its polymer PBF business was acquired by Nexa3D in 2023.

XYZprinting, Inc.
New Taipei City, Taiwan
www.xyzprinting.com

Fig. 297. Color model, courtesy of XYZprinting

Model name *MEX*	Build volume, mm (in)	Materials	~Base x 1,000
PartPro200 xTCS (full color)	185 x 185 x 150 (7.2 x 7.2 x 5.9)	PLA, PETG, carbon fiber	–
PartPro200 xTCS (mono color)	200 x 200 x 150 (7.9 x 7.9 x 5.9)	same as above	–
PartPro300 xT (single extruder)	195 x 270 x 300 (7.7 x 10.6 x 11.8)	ABS, PLA, PETG, PC, carbon- and metal-filled PLA, soluble support	–
PartPro300 xT (dual extruder)	295 x 300 x 300 (11.6 x 11.8 x 11.8)	same as above	–
BJT			
PartPro350 xBC	350 x 222 x 200 (13.8 x 8.7 x 7.9)	full-color composite	$30
PBF (polymer)			
MfgPro230 xS	230 x 230 x 230 (9.1 x 9.1 x 9.1)	PA12, TPU	$60
MfgPro236 xS	230 x 230 x 250 (9.1 x 9.1 x 9.8)	PA12, PA11, carbon-fiber PA11, PA6, reinforced PA6, TPU	–
VPP			
PartPro100 xP	64 x 40 x 120 (2.5 x 1.6 x 4.7)	photopolymer	–
PartPro120 xP	114 x 64 x 100 (4.5 x 2.5 x 4)	same as above	–
PartPro150 xP	150 x 150 x 200 (5.9 x 5.9 x 7.9)	same as above	–

ZRapid

ZRapid, founded in 2011, manufactures a wide range of machines, including metal and polymer PBF systems.

ZRapid Technologies Co., Ltd.
Suzhou, China
www.zero-tek.com

Fig. 298. Propeller printed on iSLM280, courtesy of ZRapid

Model name *VPP*	Build volume, mm (in)	Materials	~Base x 1,000
iSLA200	200 x 160 x 150 (7.9 x 6.3 x 5.9)	photopolymer	–
iSLA300	300 x 300 x 200 (11.8 x 11.8 x 7.9)	same as above	–
iSLA450	450 x 450 x 300 (17.7 x 17.7 x 11.8)	same as above	–
iSLA500	500 x 400 x 300 (19.7 x 15.7 x 11.8)	same as above	–
iSLA550	500 x 500 x 300 (19.7 x 19.7 x 11.8)	same as above	–
iSLA550Lite	500 x 500 x 300 (19.7 x 19.7 x 11.8)	same as above	–
iSLA550Ex	500 x 500 x 300 (19.7 x 19.7 x 11.8)	same as above	–
iSLA660	600 x 600 x 300 (23.6 x 23.6 x 11.8)	same as above	–
iSLA660Lite	600 x 600 x 300 (23.6 x 23.6 x 11.8)	same as above	–
iSLA6036	600 x 360 x 300 (23.6 x 14.2 x 11.8)	same as above	–
iSLA880	800 x 800 x 400 (31.5 x 31.5 x 15.7)	same as above	–
iSLA1100	1,000 x 1,000 x 600 (39.4 x 39.4 x 23.6)	same as above	–
iSLA1100D	1,000 x 1,000 x 600 (39.4 x 39.4 x 23.6)	same as above	–
iSLA1300D	1,300 x 750 x 600 (51.2 x 29.5 x 23.6)	same as above	–
iSLA1400D	1,400 x 800 x 600 (55.1 x 31.5 x 23.6)	same as above	–
iSLA1600D	1,600 x 800 x 600 (63 x 31.5 x 23.6)	same as above	–
iSLA1900D	1,900 x 1,000 x 600 (70.9 x 39.4 x 23.6)	same as above	–
iAMC200	200 x 200 x 200 (7.9 x 7.9 x 7.9)	alumina, zirconia	–
PBF (metal)			
iSLM100	110 x 110 x 100 (4.3 x 4.3 x 3.9)	stainless steel, tool steel, titanium, aluminum, cobalt-chrome, nickel alloy, copper	–

iSLM160	160 x 160 x 230 (6.3 x 6.3 x 9)	same as above	–
iSLM280	280 x 280 x 350 (11 x 11 x 13.8)	same as above	–
iSLM420	420 x 420 x 450 (16.5 x 16.5 x 17.7)	same as above	–
iSLM420D	420 x 420 x 450 (16.5 x 16.5 x 17.7)	same as above	–
iSLM500D	500 x 400 x 800 (19.7 x 15.7 x 31.5)	same as above	–
iSLM600QN	600 x 600 x 1,000 (23.6 x 23.6 x 39.4)	same as above	–
iSLM800QN	800 x 700 x 1,000 (31.5 x 27.6 x 39.4)	same as above	–
iDEN160	160 x 160 x 100 (6.3 x 6.3 x 3.9)	titanium, cobalt-chrome	–
PBF (polymer)			
iSLS300	300 x 300 x 300 (11.8 x 11.8 x 11.8)	PA12	–
iSLS400	400 x 400 x 400 (15.7 x 15.7 x 15.7)	same as above	–

Germany

Several prominent producers of AM systems are located in Germany. The country holds a prominent position, especially in metal AM.

Arburg

Arburg, an established manufacturer of injection-molding machines, produces AM systems that form parts from thermoplastic pellets.

ARBURG GmbH + Co KG
Lossburg, Germany
www.arburg.com

Fig. 299. Surgical implant (green), courtesy of Arburg

Model name *MEX (variant)*	Build volume, mm (in)	Materials	~Base x 1,000
Freeformer 200-3x	154 x 134 x 230 (6.1 x 5.3 x 9.1)	standard thermoplastic pellets/ granulates	€150

Freeformer 300-3x	234 x 134 x 230 (9.2 x 5.2 x 9.0)	same as above	–
Freeformer 700-3x	330 x 230 x 230 (13 x 9 x 9)	same as above	–

BigRep

BigRep produces large MEX machines and partners with material suppliers.

BigRep GmbH
Berlin, Germany
www.bigrep.com

Fig. 300. Custom center console for a car, courtesy of BigRep

Model name *MEX*	**Build volume, mm (in)**	**Materials**	**~Base x 1,000**
BigRep ONE	1,005 x 1,005 x 1,005 (39.6 x 39.6 x 39.6)	PLA, PVA, PETG, PRO HT, TPU, PLX, soluble support	€52.5
BigRep STUDIO G2	1,000 x 500 x 500 (39.4 x 19.7 x 19.7)	PLA, PA6, PA66, ABS, ASA, PET-CF, TPU, PVA, PETG, PRO HT, PLX, soluble support	€52.5
BigRep PRO	1,200 x 970 x 985 (47.2 x 38.2 x 38.8)	PA6, PA66, ASA, PETG, PRO HT, soluble support	€165

DMG Mori

DMG Mori is a German-Japanese producer of hybrid AM systems that integrate CNC cutting tools and DED. The company also offers PBF systems.

DMG Mori Co., Ltd.
Bielefeld, Germany
www.dmgmori.com

Fig. 301. Turbine housing, courtesy of DMG Mori

Model name	Build volume, mm (in)	Materials	~Base x 1,000
PBF (metal)			
LASERTEC 12 SLM	125 x 125 x 200 (4.9 x 4.9 x 7.9)	aluminum, stainless steel, titanium, cobalt-chrome, tool steel, nickel alloy, copper, and copper alloy	–
LASERTEC 30 DUAL SLM	300 x 300 x 300 (11.8 x 11.8 x 11.8)	same as above	–
DED			
LASERTEC 65 DED	735 x 650 x 560 (28.9 x 25.6 x 22)	stainless steel, duplex steels, tool steels, high-speed steels, nickel alloys, copper alloys, cobalt alloys, aluminum, noble metal alloys	–
DED (hybrid)			
LASERTEC 65 DED Hybrid	735 x 650 x 560 (28.9 x 25.6 x 22)	stainless steel, duplex steels, tool steels, high-speed steels, nickel alloys, copper alloys, cobalt alloys	–
LASERTEC 125 DED Hybrid	1,336 x 1,250 x 750 (52.6 x 49.2 x 35.4)	same as above	–
LASERTEC 3000 DED Hybrid	670 dia. x 932 (26.4 dia. x 36.7)	same as above	–
	400 dia. x 1,321 (15.7 dia. x 52)	same as above	–
LASERTEC 6600 Hybrid	1,040 x 330 x 3,890 (40.9 x 13 x 153.1)	same as above	–

EOS

EOS is a privately held manufacturer of PBF systems and materials and offers related consulting services.

EOS GmbH
Krailling, Germany
www.eos.info

Fig. 302. Titanium motocross footrest, courtesy of Pankl and EOS

Model name *PBF (polymer)*	Build volume, mm (in)	Materials	~Base x 1,000
FORMIGA P 110 Velocis	200 x 250 x 330 (7.9 x 9.8 x 13)	PA12, glass- and aluminum-filled PA12, PA11, PP	€130
FORMIGA P 110 FDR	200 x 250 x 330 (7.9 x 9.8 x 13)	PA11	€200
EOS P 396	340 x 340 x 600 (13.4 x 13.4 x 23.6)	PA12, glass- and aluminum-filled PA12, fire-retardant PA12, PA11, carbon-filled PA11, fire-retardant PA11, PP, TPU	€267
Integra P 450 (U.S. only)	420 x 420 x 500 (16.5 x 16.5 x 19.7)	PA12, glass-filled PA12, PA11	€350
EOS P 500	500 x 330 x 400 (19.7 x 13 x 15.7)	PA12	€650
EOS P 770	700 x 380 x 580 (27.6 x 15 x 22.9)	PA12, glass- and aluminum-filled PA12, fire-retardant PA12, PA11, TPU	€632
PBF (metal)			
EOS M 290	250 x 250 x 325 (9.8 x 9.8 x 12.8)	cobalt-chrome, titanium, case hardening steel, stainless steel, maraging steel, tool steel, nickel alloy, aluminum, copper	€480
EOS M 300-4	300 x 300 x 400 (11.8 x 11.8 x 15.8)	maraging steel, nickel alloy, titanium, stainless steel, aluminum	€1,000
EOS M 400	400 x 400 x 400 (15.8 x 15.8 x 15.8)	aluminum, titanium, maraging steel, nickel alloy, copper	€1,250
EOS M 400-4	400 x 400 x 400 (15.8 x 15.8 x 15.8)	aluminum, stainless and maraging steels, case hardening steels, titanium, nickel alloy	€1,420

SLM Solutions

SLM Solutions is a publicly traded manufacturer of metal PBF machines. It was acquired by Nikon in January 2023.

SLM Solutions
Lübeck, Germany
www.slm-solutions.com

Fig. 303. Krueger flap actuator bracket, courtesy of Asco Industries and SLM Solutions

Model name *PBF (metal)*	Build volume, mm (in)	Materials	~Base x 1,000
SLM 125	125 x 125 x 125 (4.9 x 4.9 x 4.9)	aluminum alloys, titanium alloys, nickel alloys, cobalt alloys, copper alloys, tool steels, stainless steels, iron alloys	–
SLM 280 2.0	280 x 280 x 365 (11 x 11 x 14.4)	same as above	–
SLM 280 Production Series	280 x 280 x 365 (11 x 11 x 14.4)	same as above	–
SLM 500	500 x 280 x 365 (19.7 x 11 x 14.4)	same as above	–
SLM 800	500 x 280 x 850 (19.7 x 11 x 33.5)	same as above	–
NXG XII 600	600 x 600 x 600 (23.6 x 23.6 x 23.6)	aluminum alloys, titanium alloys, nickel alloys	–
NXG XII 600 E	600 x 600 x 1500 (23.6 x 23.6 x 63)	aluminum alloys, titanium alloys, nickel alloys	–

Trumpf

Trumpf has manufactured optical systems since 1923 and offers metal PBF and DED systems.

Trumpf SE + Co. KG
Ditzingen, Germany
www.trumpf.com

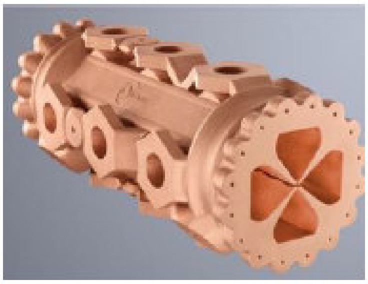


Fig. 304. Fig: 1: Radio-frequency quadrupole for a particle accelerator printed in pure copper on a TruPrint 5000 Green Edition, courtesy of Trumpf

Model name *PBF (metal)*	Build volume, mm (in)	Materials	~Base x 1,000
TruPrint 1000 Basic Edition	100 dia. x 100 (3.9 dia. x 3.9)	stainless steel, tool steel, cobalt-chrome, aluminum, nickel alloys, copper, titanium alloy, precious metals, amorphous metals	
TruPrint 1000	100 dia. x 100 (3.9 dia. x 3.9)	stainless steel, tool steel, cobalt-chrome, aluminum, nickel alloys, copper, titanium alloy, precious metals, amorphous metals	–

TruPrint 2000	200 dia. x 200 (7.8 dia. x 7.8)	stainless steel, tool steel, cobalt-chrome, aluminum, nickel alloys, titanium alloy, amorphous metals, tungsten	–
TruPrint 3000	300 dia. x 400 (11.8 dia. x 15.8)	stainless steel, tool steel, aluminum, nickel alloys, titanium alloy	–
TruPrint 5000	300 dia. x 400 (11.8 dia. x 15.8)	same as above	–
	290 dia. x 390 (11.4 dia. x 15.4)	stainless steel, tool steel, aluminum, nickel alloys, titanium alloy, Ti6242, H11 and H13 tool steel	–
TruPrint 5000 Green Edition	300 dia. x 400 (11.8 dia. x 15.8)	copper, copper alloys, aluminum alloys	
DED			
TruLaser Cell 3000	800 x 600 x 400 (31 x 23.6 x 16)	tool steels, stainless steel, carbides and matrices, aluminum alloys, titanium alloys, nickel alloys, copper alloys	–
TruLaser Cell 7040	4,000 x 1,500 x 750 (157 x 59 x 30)	same as above	–
	4,000 x 2,000 x 750 (157 x 79 x 30)	same as above	–

Voxeljet

Voxeljet manufactures large industrial BJT systems for investment casting patterns and sand-casting molds and cores, as well as PBF systems for functional prototypes.

Voxeljet AG
Friedberg, Germany
www.voxeljet.com

Fig. 305. VX4000 printer with impeller core (left) and boat propeller printed in PMMA and investment cast and polished (right), courtesy of Voxeljet

Model name *BJT*	**Build volume, mm (in)**	**Materials**	**~Base x 1,000**
VX200	300 x 200 x 150 (11.8 x 7.9 x 5.9)	PMMA, sand, ceramic	€167
VX1000	1,000 x 600 x 500 (41.7 x 23.6 x 19.7)	same as above	€485
VX1300	1,300 x 600 x 200 (51.2 x 23.6 x 7.9)	sand	€890
VX2000	2,000 x 1,000x1,000 (78.7 x 39.4 x 39.4)	same as above	€776
VX4000	4,000 x 2,000 1,000 (157.5 x 78.7 x 39.4)	same as above	€1,411

PBF (polymer)			
VX200	290 x 140 x 180 (11.4 x 5.5 x 7.1)	PA12, PP, TPU, EVA, HDPE, PEBA, PA6, PA11, PET, PBT, UHMWPE, PA12GF, TPE	€196
VX1000	1,000 x 540 x 400 (41.7 x 21.3 x 15.8)	PA12	€781

Other companies in Europe and the Middle East

Many companies in Europe and the Middle East manufacture industrial AM systems.

Additive Industries

Additive Industries produces automated and modular metal PBF systems that can automate up to eight builds without operator intervention.

Additive Industries B.V.
www.additiveindustries.com

Fig. 306. 150-kg (330-lb) aerospace part, courtesy of Additive Industries

Model name *PBF (metal)*	**Build volume, mm (in)**	**Materials**	**~Base x 1,000**
MetalFABG2 Core	420 x 420 x 400 (16.5 x 16.5 x 15.8)	stainless steel, tool steel, aluminum alloy, titanium alloy, nickel alloys	€895
MetalFABG2 Automation	420 x 420 x 400 (16.5 x 16.5 x 15.8)	same as above	€1,750
MetalFABG2 Continuous Production	420 x 420 x 400 (16.5 x 16.5 x 15.8)	same as above	€2,186

AddUp

AddUp, a joint venture between Michelin and Fives, produces metal PBF and DED machines. AddUp acquired BeAM in 2018.

AddUp
Cébazat, France
www.addupsolutions.com

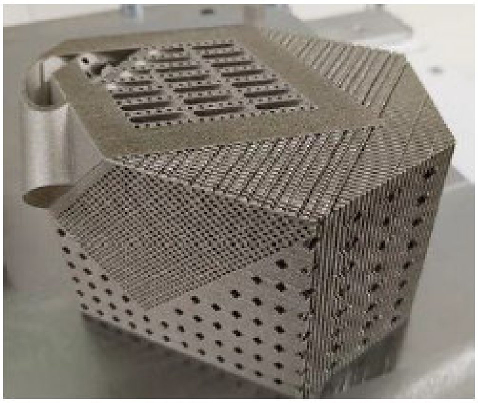


Fig. 307. Section of a heat exchanger, courtesy of AddUp

Model name *PBF (metal)*	Build volume, mm (in)	Materials	~Base x 1,000
FormUp 350	350 x 350 x 350 (13.8 x 13.8 x 13.8)	stainless steel, maraging steel, aluminum alloys, Inconel, titanium, aluminum	€1,000
DED			
Modulo 400	600 x 400 x 400 (23.6 x 15.7 x 15.7)	stainless steel, titanium alloys, Inconel alloys, Stellite, tool steels, Waspalloy, Hatfield steel, copper alloys	–
Magic 800	1,200 x 800 x 800 (47.2 x 31.5 x 31.5)	same as above	€900–1,300

Admatec

Admatec produces VPP machines, furnaces, and resins for producing ceramic and metal parts.

Admatec BV
Alkmaar, Netherlands
www.admateceurope.com

Fig. 308. Ceramic instrument for optical interferometry, courtesy of Admatec

Model name *VPP*	Build volume, mm (in)	Materials	~Base x 1,000
Admaflex 130	160 x 100 x 400 (6.3 x 3.9 x 15.7)	aluminum oxide, zirconium oxide, silica, alumina, cordierite, steatite, SiAlON, silicon carbide, hydroxyapatite, stainless steel, Inconel 625, copper	$145
Admaflex 300	260 x 220 x 500 (10.2 x 8.7 x 19.7)	same as above	$320
Admaflex 300 MultiMaterial	102 x 64 x 100 (4.0 x 2.5 x 3.9)	same as above with two materials simultaneously	$440

Digital Metal

Digital Metal was formerly owned by Höganäs and was acquired by Markforged in 2022. The company produces BJT systems for printing small, complex metal parts.

Digital Metal
Höganäs, Sweden
www.digitalmetal.tech

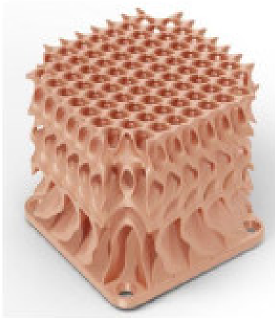


Fig. 309. Copper heat sink, courtesy of Digital Metal

Model name *BJT*	Build volume, mm (in)	Materials	~Base x 1,000
DM P2500	250 x 217 x 70 (9.8 x 8.5 x 2.8)	stainless steel, titanium alloy, DM625 and DM247 superalloys, tool steel, copper	–
	250 x 217 x 186 (9.8 x 8.5 x 7.3)	same as above	€495
DMP/Pro	250 x 217 x 70 (9.8 x 8.5 x 2.8) 250 x 217 x 186 (9.8 x 8.5 x 2.8)	same as above	–

DWS

DWS manufactures VPP systems for jewelry, dental, and general engineering applications.

DWS srl
Thiene, Italy
www.dwssystems.com

Fig. 310. DWS system (left) and Flexa Digital TPU material (right), courtesy of DWS

Model name *VPP*	Build volume, mm (in)	Materials	~Base x 1,000
XFab 2500SD	180 dia. x 180 (7.1 dia. x 7.1)	photopolymer	€7
XFab 2500HD	180 dia. x 180 (7.1 dia. x 7.1)	same as above	€9
XFab 2500PD	180 dia. x 180 (7.1 dia. x 7.1)	same as above	€9
XFab 3500SD	140 x 140 x 180 (5.5 x 5.5 x 7.1)	same as above	€14
XFab 3500HD	140 x 140 x 180 (5.5 x 5.5 x 7.1)	same as above	€19
XFab 3500PD	160 x 160 x 180 (6.3 x 6.3 x 7.1)	same as above	€24
LFAB	50 x 20 x 40 (2 x 0.8 x 1.6)	same as above	€20
DFAB Desktop	50 x 20 x 40 (2 x 0.8 x 1.6)	same as above	€34
DFAB Chairside	50 x 20 x 40 (2 x 0.8 x 1.6)	same as above	€39
DW 028XLHR	100 x 100 x 100 (3.93 x 3.93 x 3.93)	same as above	€26,5
DW 029JL2	110 x 110 x 100 (4.3 x 4.3 x 2.8)	same as above	€70
DW 029X	150 x 150 x 100 (5.9 x 5.9 x 3.9)	same as above	€89
DW 029XC	170 x 170 x 200 (6.7 x 6.7 x 7.9)	same as above	€98
XPRO S	300 x 300 x 300 (11.8 x 11.8 x 11.8)	same as above	€110
XPRO SL	300 x 300 x 500 (11.8 x 11.8 x 19.7)	same as above	€140
XPRO Q	300 x 300 x 300 (11.8 x 11.8 x 11.8)	same as above	€280

Lithoz

Lithoz produces VPP systems and materials for engineering and bioresorbable ceramics. In 2022, Lithoz launched a second process called Laser-Induced Slipcasting for producing larger, fully dense, and dark ceramic parts.

Lithoz GmbH
Vienna, Austria
www.lithoz.com

Fig. 311. Bone replacement implants made of bioresorbable hydroxyapatite, courtesy of Lithoz

Model name *VPP*	Build volume, mm (mm/in)	Materials	~Base x 1,000
CeraFab Lab L30	76 x 43 x 170 (3 x 1.7 x 6.7)	alumina, zirconia, alumina-zirconia composites, tricalcium phosphate, silica-based materials, silicon nitride, aluminum nitride, cordierite, magnesia, dielectric ceramics, hydroxyapatite, lithium disilicate bioglass, glass-ceramics, piezoceramics	-
CeraFab System S25	64 x 40 x 320 (2.5 x 1.6 x 12.6)	same as above	–
CeraFab System S65	102 x 64 x 320 (4 x 2.5 x 12.6)	same as above	–
CeraFab System S230	192 x 120 x 320 (7.6 x 4.7 x 12.6)	same as above	–
CeraFab System S65 Medical	102 x 64 x 320 (4 x 2.5 x 12.6)	aluminum oxide, hydroxyapatite, silicon nitride, tricalcium phosphate, zirconium oxide	–
CeraFab Multi 2M30	76 x 43 x 170 (3 x 1.7 x 6.7)	ceramics, metals, polymers	–
CeraMax Vario V900	250 x 250 x 290 (9.8 x 9.8 x 11.4)	water-based ceramic materials, silicon carbide	–

Prodways

Prodways offers AM systems using its proprietary MovingLight, Rapid Additive Forging, and other processes.

Prodways Technologies
Les Mureaux, France
www.prodways.com

Fig. 312. Master pattern for casting, courtesy of Prodways

Model name *VPP*	Build volume, mm (in)	Materials	~Base x 1,000
ProMaker LD10 Dental Models	300 x 445 x 200 (11.8 x 17.5 x 7.9)	photopolymers	€99
ProMaker LD10 Dental Plus	300 x 445 x 200 (11.8 x 17.5 x 7.9)	same as above	€99
ProMaker LD20 Dental Models	300 x 445 x 200 (11.8 x 17.5 x 7.9)	same as above	€129
ProMaker LD20 Dental Plus	300 x 445 x 200 (11.8 x 17.5 x 7.9)	same as above	€129
PBF (polymer)			
ProMaker P1000	300 x 300 x 300 (11.8 x 11.8 x 11.8)	same as above	–
ProMaker P1000 X	300 x 300 x 360 (11.8 x 11.8 x 14.2)	same as above	€135
ProMaker P1000 S	300 x 300 x 360 (11.8 x 11.8 x 14.2)	same as above	–
DED			
ProMaker RAF 50	1,200 x 800 x 500 (47.2 x 31.5 x 19.7)	aluminum, stainless steel, nickel-based steels, tool steels	–

Renishaw

Renishaw has produced coordinate measurement machines since 1973, and metal PBF machines for more than a decade.

Renishaw plc
New Mills, England
www.renishaw.com

Fig. 313. Microturbine recuperator, courtesy of Renishaw

Model name *PBF (metal)*	Build volume, mm (in)	Materials	~Base x 1,000
RenAM 500S	250 x 250 x 350 (9.8 x 9.8 x 13.8)	stainless steel, aluminum alloy, titanium alloy, cobalt-chrome, nickel alloy	£430 ($565)
RenAM 500Q	250 x 250 x 350 (9.8 x 9.8 x 13.8)	stainless steel, tool steel, aluminum alloy, titanium alloy, cobalt-chrome, nickel alloy, maraging steel	£655 ($860)
RenAM 500 Flex	250 x 250 x 350 (9.8 x 9.8 x 13.8)	same as above	–

Sinterit

Sinterit produces relatively low-cost polymer PBF systems.

Sinterit sp. z o.o.
Kraków, Poland
www.sinterit.com

Fig. 314. Lighting fixture produced on Lisa PRO, courtesy of STUCCHI and Sinterit

Model name *PBF (polymer)*	Build volume, mm (in)	Materials	~Base x 1,000
Lisa	110 x 160 x 130 (4.3 x 6.3 x 5.1)	PA12	€6
	110 x 160 x 145 (4.3 x 6.3 x 5.7)	TPU	
Lisa PRO	110 x 160 x 230 (4.3 x 6.3 x 9)	PA12, PA11, PP	€12
	110 x 160 x 245 (4.3 x 6.3 x 9.6)	TPU	
Lisa X	130 x 180 x 330 (5.1 x 6.7 x 13.3) 130 x 180 x 340 (5.1 x 7.1 x 13.3)	PA12, PA11, PP TPU	–
NILS 480	200 x 200 x 330 (7.9 x 7.9 x 13)	same as above	–

Sisma

Sisma is a manufacturer of laser marking, welding, and cutting machines, and offers VPP and metal PBF systems. In 2021, Sisma sold its share in the metal PBF joint venture business to Trumpf.

Sisma S.p.A.
Vicenza, Italy
www.sisma.com

Fig. 315. Jewelry application, courtesy of Sisma

Model name *PBF (metal)*	Build volume, mm (in)	Materials	~Base x 1,000
MYSINT 100	100 dia. x 100 (3.9 dia. x 3.9)	precious metals, titanium alloy, cobalt-chrome, steel alloys, aluminum, nickel alloy, copper alloy, bronze	–
MYSINT 100 PM	100 dia. x 100 (3.9 dia. x 3.9)	same as above	–
MYSINT 100 RM	100 dia. x 100 (3.9 dia. x 3.9)	same as above	–
MYSINT 100 PM/RM	100 dia. x 100 (3.9 dia. x 3.9)	same as above	–
MYSINT 100 Dual Laser	100 dia. x 100 (3.9 dia. x 3.9)	same as above	–
MYSINT 200	200 dia. x 200 (7.8 dia. x 7.8)	precious metals, titanium alloy, cobalt-chrome, steel alloys, aluminum, nickel alloy	–
VPP			
EVERES ZERO	96 x 54 x 200 (3.8 x 2.1 x 7.9)	photopolymers, casting resin, moldable resin	–
EVERES UNO	125 x 70 x 200 (4.9 x 2.8 x 7.9)	same as above	–

Stratasys

Industry pioneer Stratasys, which merged with Objet in 2012, produces MEX, MJT, PBF, and VPP systems. In December 2020, Stratasys acquired Origin, a manufacturer of VPP systems.

Stratasys
Rehovot, Israel
www.stratasys.com

Fig. 316. 3D-printed medical models, courtesy of Stratasys

Model name	Build volume, mm (in)	Materials	~Base x 1,000
MEX			
F120	254 x 254 x 254 (10 x 10 x 10)	ABS, ASA	$12
F170	254 x 254 x 254 (10 x 10 x 10)	PLA, ABS, ASA, TPU	$20
F270	305 x 254 x 305 (12 x 10 x 12)	same as above	$40
F370	355 x 254 x 355 (14 x 10 x 14)	same as above	$60
F770	1,000 x 610 x 610 (39 x 24 x 24)	ABS, ASA	–

Model name	Build volume, mm (in)	Materials	~Base x 1,000
F900	914 x 610 x 914 (36 x 24 x 36)	ASA, ABS, PC, PA6, PA12, Antero, PPSU, PPSF, ULTEM, carbon-fiber PA12	$400
Fortus 450mc	406 x 355 x 406 (16 x 14 x 16)	ASA, ABS, PC, PC-ABS, PA12, ULTEM, Antero, carbon-fiber PA12, Nylon , ST-130	$150
MJT			
Objet30	294 x 192 x 149 (11.6 x 7.6 x 5.9)	VeroWhite, VeroBlack, VeroBlue, VeroGrey, DraftGrey VeroClear, PP, elastomers	–
Objet30 Pro	300 x 200 x 150 (11.8 x 7.9 x 5.9)	Vero and VeroVivid color materials, Agilus30 flexible materials, VeroClear and VeroUltraClear	$25
Objet30 Prime	300 x 200 x 150 (11.8 x 7.9 x 5.9)	same as above	$38
Objet260 Connex3	260 x 260 x 200 (10.2 x 10.2 x 7.9)	same as above	$100
Objet500 Connex3	500 x 400 x 200 (19.7 x 15.7 x 7.9)	same as above	$216
Objet1000 plus	1,000 x 800 x 500 (39.4 x 31.5 x 9.7)	VeroClear, TangoPlus and TangoBlackPlus, Vero color, Rigur (simulated polypropylene)	$500
Objet30 Dental Prime	300 x 200 x 150 (11.8 x 7.9 x 5.9)	acrylic, dental, and biocompatible photopolymers	$35
Objet260 Dental Selection	500 x 400 x 200 (19.7 x 15.7 x 7.9)	same as above	$119
Objet500 Dental Selection	500 x 400 x 200 (19.7 x 15.7 x 7.9)	same as above	$184
J35 Pro	174^2 x 158 (18.2^2 x 6.22)	Vero Draft Grey, VeroUltraClear, Elastico, Digital ABS.	–
J55	140 x 200 x 190 (5.5 x 7.9 x 7.5)	Vero Draft Grey, Vero and VeroVivid color materials, VeroClear and VeroUltraClear	–
J826 Prime	255 x 252 x 200 (10.0 x 9.9 x 7.9)	Vero and VeroVivid color materials, Agilus30 flexible materials, VeroClear and VeroUltraClear, Digital ABS	
J850	490 x 390 x 200 (19.3 x 15.6 x 7.9)	same as above	$350
J3 DentaJet	140 x 200 x 190 (5.5 x 7.9 x 7.5)	Vero, Vero Glaze, biocompatible materials	–
J5 DentaJet	140 x 200 x 190 (5.5 x 7.9 x 7.5)	Vero, Vero color, Vero Glaze, biocompatible materials	–
J5 MediJet	140 x 200 x 190 (5.5 x 7.9 x 7.5)	Vero, Vero color, Vero Glaze, biocompatible materials	–
J700 Dental	490 x 390 x 200 (19.3 x 15.4 x 7.9)	acrylic and dental photopolymers	$184
J720 Dental	490 x 390 x 200 (19.3 x 15.4 x 7.9)	Vero color materials, Tango and Agilus30 flexible materials, VeroClear	$184
J750 Dental	490 x 390 x 200 (19.3 x 15.4 x 7.9)	Vero and VeroVivid color materials, Agilus30 flexible material, VeroClear and VeroUltraClear, TissueMatrix, BoneMatrix	$369
J750 Digital Anatomy	490 x 390 x 200 (19.3 x 15.6 x 7.9)	Vero and VeroVivid color materials, Agilus30 flexible materials, TissueMatrix, biocompatible clear	$350
J850 Digital Anatomy	490 x 390 x 200 (19.3 x 15.6 x 7.9)	Vero and VeroVivid color materials, Agilus30 flexible materials, TissueMatrix, biocompatible clear	–
J850 TechStyle	460 x 360 x 50 (18.1 x 14.2 x 1.9)	Vero and VeroVivid color materials, Agilus30 flexible materials, Transparent VeroClear	–

Model name	Build volume, mm (in)	Materials	~Base x 1,000
J850 Prime	490 x 390 x 200 (19.3 x 15.6 x 7.9)	Vero and VeroVivid color materials, Agilus30 flexible materials, VeroClear and VeroUltraClear, Digital ABS	–
J850 Pro	490 x 390 x 200 (19.3 x 15.6 x 7.9)	Vero color materials, Agilus30 flexible materials, VeroClear and VeroUltraClear, Digital ABS	–
PBF (polymer)			
J4100	1000 x 800 x 500 (39.4 x 31.5 x 19.7)	Vero color materials, Agilus30 flexible materials, VeroClear and VeroUltraClear, Digital ABS	–
H350	315 x 208 x 293 (12.4 x 8.2 x 11.5)	PA11, PA12	–
VPP			
V650 Flex	508 x 584 x 508 (20 x 23 x 20)	Somos Element, Somos NeXt, Somos PerFORM, and Somos Watershed XC 11122 resins	$299
Origin One	192 x 108 x 370 (7.5 x 4.3 x 14.5)	photopolymers	–
Origin One Dental	192 x 108 x 370 (7.5 x 4.3 x 14.5)	dental focused photopolymers	–
Neo450e/s	450 × 450 × 400 (17.7× 17.7×15.7)	Open resin system - compatible with commercially available 355 nm stereolithography resins	–
Neo800	800 × 800 × 600 (31.5×31.5× 23.6)	Open resin system - compatible with commercially available 355 nm stereolithography resins	–

XJet

XJet prints a liquid suspension containing nanoparticles of ceramic or metal through inkjet print heads to produce parts with soluble supports.

XJet Ltd.
Rehovot, Israel
www.xjet3d.com

Fig. 317. 3D-printed industrial part, courtesy of XJet

Model name *MJT*	Build volume, mm (in)	Materials	~Base x 1,000
Carmel 1400C	500 x 140 x 200 (19.7 x 5.5 x 7.9)	zirconia, alumina	$729
Carmel 1400M	500 x 140 x 200 (19.7 x 5.5 x 7.9)	stainless steel	$729

U.S.

A growing number of companies in the U.S. produce industrial AM systems using a wide range of processes and materials.

3D Systems

3D Systems was the first company to commercialize AM when it launched stereolithography in 1988. It continues to provide a range of machines based on several processes obtained through acquisitions.

3D Systems, Inc.
Rock Hill, South Carolina
www.3dsystems.com

Fig. 318. Liquid rocket engine injector, courtesy of 3D Systems

Model name *VPP*	Build volume, mm (in)	Materials	~Base x 1,000
ProJet 6000 HD	250 x 250 x 250 (10 x 10 x 10)	photopolymer	$168
ProJet 7000 HD	380 x 380 x 250 (15 x 15 x 10)	same as above	$243
ProX 800	650 x 750 x 550 (25.6 x 29.5 x 21.6)	photopolymer and nanocomposite-filled plastics	$475
SLA 750	750 x 750 x 550 (29.5 x 29.5 x 21.6)	photopolymer and nanocomposite-filled plastics	$380
ProX 950	1,500 x 750 x 550 (59 x 30 x 22)	photopolymer	$990
Figure 4 Production	124.8 x 70.2 x 346 (4.9 x 2.8 x 13.6)	same as above	per config.
Figure 4 Modular	124.8 x 70.2 x 346 (4.9 x 2.8 x 13.6)	same as above	$45
Figure 4 Standalone	124.8 x 70.2 x 196 (4.9 x 2.8 x 7.7)	same as above	$20
Figure 4 Jewelry	124.8 x 70.2 x 196 (4.9 x 2.8 x 7.7)	same as above	$12

NextDent 5100	124.8 x 70.2 x 196 (4.9 x 2.8 x 7.7)	dental photopolymer	$10
MJT			
ProJet MJP 2500 Plus	(294 x 211 x 144 (11.6 x 8.3 x 5.7)	photopolymer, melt-away support material	$52
ProJet MJP 2500W RealWax printer	294 x 211 x 144 (11.6 x 8.3 x 5.7)	wax, melt-away support material	$47
ProJet MJP 2500IC	294 x 211 x 144 (11.6 x 8.3 x 5.7)	same as above	$59
ProJet MJP 3600	298 x 185 x 203 (11.8 x 7.3 x 8)	photopolymer, melt-away support material	$80
ProJet MJP 3600 Max	298 x 185 x 203 (11.8 x 7.3 x 8)	same as above	$90
ProJet MJP 3600 Dental	284 x 185 x 203 (11.2 x 7.3 x 8)	same as above	$73
ProJet MJP 3600W	298 x 185 x 203 (11.8 x 7.3 x 8)	wax, melt-away support material	$85
ProJet MJP 3600W Max	298 x 185 x 203 (11.8 x 7.3 x 8)	same as above	$98
ProJet MJP 5600	518 x 381 x 300 (20.4 x 15 x 11.8)	photopolymer, melt-away support material	$198
PBF (polymer)			
sPro 140	550 x 550 x 460 (22 x 22 x 18)	PA, reinforced plastics	$429
sPro 230	550 x 550 x 750 (22 x 22 x 30)	same as above	$508
SLS 380	381 x 330 x 460 (15 x 13 x 18)	polyamides, reinforced plastics, fire-retardant, elastomers, polystyrene	$250
PBF (metal)			
DMP Flex 100	100 x 100 x 90 (3.9 x 3.9 x 3.5)	cobalt-chrome, stainless steel	$199
DMP Dental 100	100 x 100 x 90 (3.9 x 3.9 x 3.5)	cobalt-chrome	$199
DMP Flex 200	140 x 140 x 115 (5.5 x 5.5 x 4.5)	cobalt-chrome, titanium	$265
DMP Flex 350	275 x 275 x 420 (10.8 x 10.8 x 16.5)	cobalt-chrome, stainless steel, maraging steel, aluminum, titanium, nickel alloy	$592
DMP Factory 350	275 x 275 x 420 (10.8 x 10.8 x 16.5)	stainless steel, maraging steel, aluminum, titanium, nickel alloy	$692
DMP Flex 350 Dual	275 x 275 x 420 (10.8 x 10.8 x 16.5)	titanium, aluminum alloys	$700
DMP Factory 350 Dual	275 x 275 x 420 (10.8 x 10.8 x 16.5)	same as above	$799
DMP Factory 50key0	500 x 500 x 500 (19.7 x 19.7 x 19.7)	titanium, aluminum, nickel alloy	per module
BJT			
ProJet CJP 660Pro	254 x 381 x 203 (10 x 15 x 8)	composite (full CMYK colors)	$69
ProJet CJP 860Pro	508 x 381 x 229 (20 x 15 x 9)	same as above	$114

Carbon

Carbon produces VPP systems for prototyping and series production. The company leases its systems rather than selling them to customers.

Carbon, Inc.
Redwood City, California
www.carbon3d.com

Fig. 319. Air vent for the Sián FKP 37, courtesy of Lamborghini and Carbon

Model name *VPP*	Build volume, mm (in)	Materials	~Base x 1,000
M1	141 x 79 x 326 (5.6 x 3.1 x 12.8)	photopolymer, dual cure	–
M2	189 x 118 x 326 (7.4 x 4.6 x 12.8)	same as above	$50 annually
M3	189 x 118 x 326 (7.4 x 4.6 x 12.8)	same as above	–
M3 Max	307 x 163 x 305 (12 x 6.4 x 12)	same as above	–
L1	400 x 250 x 460 (15.7 x 9.8 x 18.1)	same as above	$250 annually

Desktop Metal

Desktop Metal produces AM systems capable of printing with a wide range of materials. It acquired ETEC (formerly Envisiontec), in February 2021. Desktop Metal acquired ExOne in November 2021.

Desktop Metal, Inc.
Burlington, Massachusetts
www.desktopmetal.com

Fig. 320. Metal powder atomization nozzle, courtesy of Wall Colmonoy and Desktop Metal

Model name *MEX (metal)*	Build volume, mm (in)	Materials	~Base x 1,000
Studio System 2	300 x 200 x 200 (11.8 x 7.9 x 7.9)	stainless steels, tool steels, low-alloy steels, copper, titanium	–
BJT (metal)			
Innovent+	160 x 65 x 65 (6.3 x 2.5 x 2.5)	stainless steels, tool steels, copper, nickel alloys, cobalt chrome, titanium, aluminum, ceramics, metal composites, ceramic-metal composites	$200
Shop System 4L	350 x 220 x 50 (13.8 x 8.7 x 2)	stainless steel, cobalt chrome, nickel alloys	–
Shop System 8L	350 x 220 x 100 (13.8 x 8.7 x 3.9)	same as above	–
Shop System 12L	350 x 220 x 150 (13.8 x 8.7 x 5.9)	same as above	–
Shop System 16L	350 x 220 x 200 (13.8 x 8.7 x 7.9)	same as above	$195
X1 25Pro	400 x 250 x 250 (15.7 x 10 x 10)	stainless steels, tool steels, copper, nickel alloys, cobalt chrome, titanium, aluminum, ceramics, metal composites, ceramic-metal composites	$550
X1 160Pro	800 x 500 x 400 (31.5 x 19.7 x 15.8)	same as above	$975
Production System P-1	200 x 100 x 40 (7.9 x 3.9 x 1.6)	stainless steels, tool steels, low-alloy steels, copper, nickel alloys, titanium, aluminum	$350
Production System P-50	490 x 380 x 260 (19.3 x 15 x 10.2)	same as above	$1,000+
VPP			
D4K Pro	148 x 83 x 110 (5.8 x 3.3 x 4.3)	photopolymers	$8
Envision One	180 x 101 x 100 (7.1 x 4 x 3.9)	same as above	$18
Envision One XL	180 x 101 x 330 (7.1 x 4 x 13)	same as above	$28
P4K 35	90 x 56 x 180 (3.5 x 2.2 x 7.1)	same as above	$125
P4K 62	160 x 100 x 180 (6.3 x 3.9 x 7.1)	same as above	$125
P4K 75	192 x 120 x 180 (7.6 x 4.7 x 7.1)	same as above	$125
P4K 90	233 x 141.5 x 180 (9.2 x 5.6 x 7.1)	same as above	$125
P4K Flex	249 x 140.3 x 180 (9.9 x 5.5 x 7.1)	same as above	$125
Xtreme 8K	450 x 371 x 399 (17.7 x 14.6 x 15.7)	same as above	$225
Einstein*	190 x 107 x 102 (7.5 x 4.2 x 4)	FDA-cleared, dental, biocompatible, wax-filled, and castable photopolymers	$11
Einsten Pro XL*	249 x 140 x 165 (9.8 x 5.5 x 6.5)	same as above	$29
MEX (non-metal)			
3D-Bioplotter Starter*	260 x 220 x 70 (10.2 x 8.7 x 2.8)	PLGA, PLLA, PCL, ceramics, fibrinogen, silicones, titanium, chitosan, collagen, alginic acid	$99

3D-Bioplotter Developer*	200 x 220 x 140 (7.8 x 8.7 x 5.5)	same as above	$175
3D-Bioplotter Manufacturer*	200 x 220 x 140 (7.8 x 8.7 x 5.5)	same as above	$225
* Desktop Health-branded systems			
BJT (sand)			
S-Max Flex	1,000 x 1,900 x 1,000 (39.4 x 74.8 x 39.4)	silica sands	$380
S-Print	800 x 500 x 400 (31.5 x 19.7 x 15.7)	silica sand, ceramic beads, chromite, zircon	$700
S-Max	1,800 x 1,000 x 700 (70.9 x 39.4 x 27.6)	same as above	$980
S-Max Pro	1,800 x 1,000 x 700 (70.9 x 39.4 x 27.6)	same as above	$1,200
BJT (wood)			
Shop Forust	350 x 220 x 200 (13.8 x 8.7 x 7.9)	wood flour	$285

Essentium

Essentium creates industrial MEX systems for high-temperature thermoplastics.

Essentium, Inc.
Pflugerville, Texas
www.essentium.com

Fig. 321. Custom fixture, courtesy of Essentium

Model name *MEX*	**Build volume, mm (in)**	**Materials**	**~Base x 1,000**
HSE 180 LT	690 x 500 x 600 (27.2 x 19.7 x 23.6)	low-temperature filaments	–
HSE 180 ST	690 x 500 x 600 (27.2 x 19.7 x 23.6)	same as above	–
HSE 180 HT	690 x 500 x 600 (27.2 x 19.7 x 23.6)	high-temperature filaments	–
HSE 240 HT	430 x 350 x 375 (16.9 x 13.8 x 4.81)	same as above	–
HSE 280i HT	695 x 500 x 600 (27.4 x 19.7 x 23.6)	same as above	–

Formlabs

Formlabs produces desktop VPP and polymer PBF systems.

Formlabs, Inc.
Somerville, Massachusetts
www.formlabs.com

Fig. 322. Examples of parts produced on the Fuse 1+ machine, courtesy of Formlabs

Model name *VPP*	Build volume, mm (in)	Materials	~Base x 1,000
Form 3+	145 x 145 x 185 (5.7 x 5.7 x 7.3)	photopolymer	$3.75
Form 3B+	145 x 145 x 185 (5.7 x 5.7 x 7.3)	photopolymer	$5.9
Form 3L	200 x 335 x 300 (7.9 x 13.2 x 11.8)	photopolymer	$11
Form 3BL	200 x 335 x 300 (7.9 x 13.2 x 11.8)	photopolymer	$13
PBF (polymer)			
Fuse 1+	165 x 165 x 300 (6.5 x 6.5 x 11.8)	PA12, PA11	$28

GE Additive

GE Additive acquired Arcam and Concept Laser in 2016. The company develops and sells metal AM systems based on PBF.

General Electric Company
Boston, Massachusetts
www.ge.com/additive

Fig. 323. Metal PBF part, courtesy of GE Additive

Model name *PBF (metal)*	Build volume, mm (in)	Materials	~Base x 1,000
LPBF Mlab 100R	90 x 90 x 80 (3.5 x 3.5 x 3.2) 50 x 50 x 80 (2 x 2 x 3.2)	stainless steel, cobalt-chrome, bronze alloy, precious metals, titanium alloy, aluminum same as above	€135
LPBF Mlab 200R	100 x 100 x 100 (3.9 x 3.9 x 3.9)	stainless steel, cobalt-chrome, titanium alloy, pure titanium, aluminum, bronze, precious metals	€188

	90 x 90 x 80 (3.5 x 3.5 x 3.2)	same as above	
	50 x 50 x 80 (2 x 2 x 3.2)	same as above	
LPBF M2 Series 5	245 x 245 x 350 (9.6 x 9.6 x 13.8)	stainless steel, tool steels, cobalt-chrome, nickel alloys, aluminum, titanium, precipitation-hardening steel	Models: S, P, P1000, R
LPBF X LINE 2000R	800 x 400 x 500 (31.5 x 15.7 x 19.7)	stainless steel, aluminum, titanium, nickel alloy, cobalt chrome	€1,780
LPBF M LINE	500 x 500 x 400 (19.7 x 19.7 x 15.7)	cobalt-chrome, nickel alloy	€2,675
EBM Q10plus 2.1	200 x 200 x 200 (7.9 x 7.9 x 7.9)	titanium, cobalt-chrome, copper	€499
EBM Spectra L	350 dia. x 430 (13.8 dia. x 16.9)	titanium	€840
EBM Spectra H	250 dia. x 430 (9.8 dia. x 16.9)	titanium, titanium aluminide, nickel alloy, tool steel, mar247	€942

HP

HP offers its multi jet fusion technology as a platform for prototyping and series production applications.

HP Inc.
Palo Alto, California
www.hp.com

Fig. 324. Tooling for environmentally friendly packaging, courtesy of HP

Model name *PBF (polymer)*	Build volume, mm (in)	Materials	~Base x 1,000
Jet Fusion 4200	380 x 284 x 380 (15 x 11 x 15)	PA, TPA, TPU	–
Jet Fusion 3D 5200 series	380 x 284 x 380 (15 x 11 x 15)	PA, TPU, PP	–
Jet Fusion 5420W	380 x 284 x 380 (15 x 11 x 15)	PA	–
BJT (metal)			
Metal Jet S100	430 x 309 x 140 (16.9 x 12.2 x 5.5)	17-4 PH and 316L stainless steel	–

Markforged

Markforged designs and sells systems capable of producing composite and metal parts.

Markforged, Inc.
Watertown, Massachusetts
www.markforged.com

Fig. 325. Kevlar-reinforced fibers (yellow), courtesy of Markforged

Model name *MEX (variant)*	Build volume, mm (in)	Materials	~Base x 1,000
Onyx One	320 x 132 x 154 (12.6 x 5.3 x 6.0)	carbon-reinforced nylon	$6
Onyx Pro	320 x 132 x 154 (12.6 x 5.3 x 6.0)	carbon-reinforced nylon, fiberglass	$10
Mark Two	320 x 132 x 154 (12.6 x 5.3 x 6.0)	carbon-reinforced nylon, fiberglass, carbon fiber, Kevlar, high-temperature high-strength fiberglass	$17
X3	330 x 270 x 200 (13 x 10.6 x 7.9)	carbon-reinforced nylon, flame-retardant carbon-reinforced nylon, nylon, static-dissipative carbon-reinforced nylon	$45
X7	330 x 270 x 200 (13 x 10.6 x 7.9)	carbon-reinforced nylon, flame-retardant carbon-reinforced nylon, nylon, static-dissipative carbon-reinforced nylon, carbon fiber fiberglass, Kevlar, high-temperature high-strength fiberglass	$78
Metal X	300 x 220 x 180 (11.8 x 8.7 x 7.1)	stainless steel, tool steel, Inconel, copper	$138+
FX20	525 x 400 x 400 (20.7 x 15.7 x 15.7)	ULTEM™ Filament, carbon-reinforced nylon, flame-retardant nylon, static-dissipative carbon-reinforced nylon, carbon fiber	$240
BJT (metal)			
PX100	250 × 217 × 186 (9.8 x 8.5 x 7.3)	stainless steel, tool steel, low alloy steel, Inconel, super alloy 247, Titanium, Copper	$550+

Optomec

Optomec offers aerosol jet and laser engineered net shaping (LENS), a DED process. Some LENS systems offer hybrid capabilities.

Optomec, Inc.
Albuquerque, New Mexico
www.optomec.com

Fig. 326. LENS and aerosol jet systems, courtesy of Optomec

Model name *DED*	Build volume, mm (in)	Materials	~Base x 1,000
LENS Print Engine	integrates with a CNC machine tool or robotics system	titanium alloys, tool steel, stainless steel alloys, Inconel alloys, Hastalloy X, copper alloys, aluminum alloys, wear-resistant alloys, Stellite 21	$129
LENS CS250	250 x 250 x 250 (10 x 10 x 10)	same as above	$370
LENS CS 600	600 x 400 x 400 (23.6 x 15.7 x 15.7)	same as above	$680
LENS CS 800	800 x 600 x 600 (31.5 x 23.6 x 23.6)	same as above	$825
LENS CS 1500	900 x 1500 x 500 (35.4 x 59.1 x 19.7)	same as above	$1,900
LENS MTS 500 (Hybrid option)	500 x 325 x 500 (19.7 x 12.8 x 19.7)	same as above	$405
LENS MTS 860 (Hybrid option)	860 x 600 x 610 (33.9 x 23.6 x 24.0)	same as above	$570
HC-205 5-axis	356 x 356 x 356 (14 x 14 x 14)	same as above	$720
HC 245 5-axis	762 x 457 x 508 (30 x 18 x 20)	same as above	$957
MJT (variant)			
Aerosol Jet Print Engine	integrates with production automation platform	organic, inorganic, and nanoparticle materials, electronic metal conductors, insulators, adhesives, silver, copper, gold, platinum, polymers, biomaterials	$143
Aerosol Jet 200 (Benchtop)	200 x 200 (8 x 8)	same as above	$224
Aerosol Jet 2K (SmartGlass)	2,000 x 1,400 (80 x 56)	same as above	$495
Aerosol Jet HD2 (Semiconductor)	300 x 300 x 100 (12 x 12 x 4)	same as above	$309
Aerosol Jet Flex	350 x 250 x 200 (14 x 10 x 8)	same as above	$411
Aerosol Jet 5X (5-Axis)	200 x 300 x 200 (8 x 12 x 8)	same as above	$495

APPENDICES

Appendix A: Glossary of terms

The following are key terms and abbreviations used in this report. Most of the terms in this appendix and report conform to the ISO/ASTM 52900 terminology standard.

3D digitizing	Same as 3D scanning.
3D printer*	Machine used for 3D printing.
3D printing*	Fabrication of objects through the deposition of a material using a print head, nozzle, or another printer technology. Term often used in a non-technical context synonymously with additive manufacturing; until present times, this term has in particular been associated with machines that are low end in price and/or overall capability.
3D scanning*	Method of acquiring the shape and size of an object as a 3D representation by recording x, y, z coordinates on the object's surface and through software converting the collection of points into digital data.
3MF	Additive manufacturing file format used to describe color, textures, materials, and other characteristics of a 3D model. Ongoing development of the file format is led by the 3MF Consortium, which was initiated by Microsoft and other companies in 2015.
ABS	Acrylonitrile butadiene styrene; a thermoplastic polymer with high-impact resistance and toughness.
additive layer manufacturing	Same as additive manufacturing.
additive manufacturing*	Process of joining materials to make parts from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing and formative manufacturing methodologies; historical terms are additive fabrication, additive processes, additive techniques, additive layer manufacturing, layer manufacturing, solid freeform fabrication, and freeform fabrication.
additive process	Same as additive manufacturing.
additive system*	Additive manufacturing system, additive manufacturing equipment, machine and auxiliary equipment used for additive manufacturing.

AM	Additive manufacturing.
AMF*	Additive Manufacturing File format for communicating additive manufacturing model data including a description of the 3D surface geometry with native support for color, materials, lattices, textures, constellations, and metadata.
as built*	The state of parts made by an additive process before any post-processing, besides, if necessary, the removal from a build platform as well as the removal of support and/or unprocessed feedstock.
ASTM International	International standards organization, formerly known as American Society for Testing and Materials.
B2B	Business to business.
B2C	Business to consumer.
batch*	Defined quantity of feedstock with uniform properties and composition.
binder jetting*	Additive manufacturing process in which a liquid bonding agent is selectively deposited to join powder materials.
BJT	Binder jetting.
bounding box*	Orthogonally oriented minimum perimeter cuboid that can span the maximum extents of the points on the surface of a part.
build chamber*	Enclosed location within the additive manufacturing system where the parts are fabricated.
build envelope*	Largest external dimensions of the x-, y-, and z-axes within the build space where parts can be fabricated.
build space*	Location where it is possible for parts to be fabricated, typically within the build chamber or on a build platform.
build volume*	Total usable volume available in the machine for building parts.
CAD	Computer-aided design; the use of computers for the design of real or virtual objects.
CAE	Computer-aided engineering; CAE software offers capabilities for engineering simulation and analysis, such as determining a part's strength or heat-transfer capacity.

CAM	Computer-aided manufacturing; typically refers to systems that use surface data to drive CNC machines, such as digitally driven mills and lathes, to produce parts, molds, and dies.
ceramic	Inorganic and non-metallic crystalline material with high compression strength and low shear and tensile strength.
cermet	Material made from ceramic and metal with heat-resistance properties.
CIM	Ceramic injection molding.
CNC	Computer numerical control; computer-controlled machines include mills, lathes, and flame cutters.
CT	Computed tomography; CT scanning is a method of capturing the internal and external structure of an object using ionizing radiation. A CT scan creates a series of two-dimensional gray-scale images that can be used to construct a 3D model.
cure*	Change the physical properties of a material by means of a chemical reaction.
DED	Directed energy deposition.
DfAM	Design for additive manufacturing.
digital light processing	A display device that creates an image using an array of micromirrors; each mirror represents one or more pixels in the projected image.
direct metal deposition	A trade name used by DM3D for the company's directed energy deposition technology.
direct metal laser sintering	A trade name used by EOS for the company's metal powder bed fusion technology.
directed energy deposition*	Additive manufacturing process in which focused thermal energy is used to fuse materials by melting as they are being deposited. "Focused thermal energy" means that an energy source (e.g., laser, electron beam, or plasma arc) is focused to melt the materials being deposited.
DLP	Digital light processing, a technology developed by Texas Instruments.
DMD	Direct metal deposition.

DMLS	Direct metal laser sintering.
EBM	Electron beam melting.
EDM	Electrical discharge machining; a method of machining that removes material with a series of electrical current discharges between a tool electrode and a workpiece.
elastomer	Amorphous polymers with elasticity and low stiffness.
electron beam melting	A trade name used by GE Additive for Arcam electron-beam-based metal powder bed fusion technology.
extrusion nozzle*	Component with an orifice through which feedstock is extruded.
facet*	Three- or four-sided polygon that represents an element of a 3D polygonal mesh surface or model. Triangular facets are used in the file formats most significant to AM AMF and STL files; however, AMF files permit a triangular facet to be curved.
FDM	Fused deposition modeling.
feedstock*	Bulk raw material supplied to the additive manufacturing building process.
fully dense*	State in which the material of a fabricated part is without significant content of voids.
fused deposition modeling	A trade name used by Stratasys for the company's material extrusion technology.
fusion*	Act of uniting two or more units of material into a single unit of material.
HIP	Hot isostatic pressing.
hot isostatic pressing	Uses heat and isostatic pressure to reduce or eliminate the porosity in metals and increase the density of ceramics.
hybrid manufacturing system	Manufacturing system that uses both additive and subtractive technologies.
ISO	International Standards Organization; more widely known as the International Organization for Standardization.
laser sintering*	Powder bed fusion process used to produce objects from powdered materials using one or more lasers to selectively fuse or melt the particles at the surface, layer upon layer, in an enclosed chamber.

layer additive manufacturing	Same as additive manufacturing.
LS	Laser sintering.
machine coordinate system*	Three-dimensional coordinate system defined by a fixed point on the build platform; defined by the machine manufacturer.
maker	A member of a technology-based do-it-yourself (DIY) community.
material extrusion*	Additive manufacturing process in which material is selectively dispensed through a nozzle or orifice.
material jetting*	Additive manufacturing process in which droplets of feedstock material are selectively deposited. Example materials include photopolymer and wax.
MCAD	Mechanical computer-aided design; the use of CAD to design mechanical parts and assemblies.
MEMS	Microelectromechanical systems.
metrology	Science of measurement.
MEX	Material extrusion.
MIM	Metal injection molding.
MJF	Multi jet fusion technology from HP.
MJT	Material jetting.
MRI	Magnetic resonance imaging; alternative to CT scanning that offers better soft-tissue contrast; MRI does not use ionizing radiation.
multi-step process*	Additive manufacturing process in which parts are fabricated in two or more operations; the first step typically provides the basic geometric shape, and the following consolidates the part to the fundamental properties of the intended material.
near net shape*	Condition where the parts require little post-processing to meet dimensional tolerance.
nesting*	Situation when parts are made in one build cycle and are located such that their bounding boxes, arbitrarily oriented or otherwise, overlap.
NSF	National Science Foundation; U.S. government funding agency.
OEM	Original equipment manufacturer.

PA	Polyamide; a family of thermoplastic polymers often used for powder bed fusion systems.
PAEK	Polyaryletherketone; a high-melting-temperature thermoplastic polymer; a member of the polyaryletherketone family.
PBF	Powder bed fusion.
PBT	Polybutylene terephthalate; a strong thermoplastic polymer used as an insulator and is resistant to solvents.
PC	Polycarbonate; a family of thermoplastic polymers that are highly formable with high-impact resistance.
PCL	Polycaprolactone; biodegradable polyester used to produce specialty polyurethanes.
PEEK	Polyether ether ketone; a high-melting-temperature thermoplastic polymer; a member of the polyaryletherketone family.
PEI	Polyethylenimine; a polymer used for adhesives, detergents, and cosmetics.
PEKK	Polyetherketoneketone; a high-melting-temperature thermoplastic polymer; a member of the polyaryletherketone family.
PHA	Polyhydroxyalkanoate; polyesters produced naturally from bacterial fermentation of lipids or sugar; biodegradable and used to produce bioplastics.
photopolymer	A thermoset polymer that changes properties when exposed to ultraviolet or visible light; typically, a photopolymer changes from liquid to solid during photopolymerization.
PIM	Plastic injection molding; popular method of molding parts from thermoplastic materials such as polypropylene, polyamide (nylon), polycarbonate, ABS, polyethylene, and polystyrene.
PLA	Polylactic acid; a thermoplastic polymer that is biodegradable and often derived from renewable sources such as corn starch, sugar cane, or tapioca roots.
PLLA	Poly-L-lactic acid (see PLA).
PMMA	Polymethyl methacrylate; a thermoplastic polymer used in Voxeljet's binder jetting process.

polymer	Material made up of large molecules that consist of repeating molecular units.
porosity*	Presence of small voids in a part, making it less than fully dense; typically quantified as a ratio and expressed as a percentage.
post-processing*	One or more process steps taken after the completion of an additive manufacturing build cycle to achieve the desired properties in the final product.
powder bed fusion*	Additive manufacturing process in which thermal energy selectively fuses regions of a powder bed.
PP	Polypropylene; a thermoplastic polymer used in a range of applications.
PPS	Polyphenylene sulfide; an organic polymer often used for making filter fabric.
process parameters*	Operating parameters and system settings used during a build cycle.
production run*	All parts produced in one build cycle or sequential series of build cycles using the same feedstock batch and process conditions.
prototype*	Physical representation of all or a component of a product that, although limited in some way, can be used for analysis, design, and evaluation.
prototype tooling*	Molds, dies, and other devices used for prototyping purposes; sometimes referred to as bridge tooling or soft tooling.
rapid prototyping*	Application of additive manufacturing intended for reducing the time needed for producing prototypes. Historically, rapid prototyping (RP) was the first commercially significant application for additive manufacturing and has therefore been commonly used as a general term for this type of technology.
rapid tooling*	Application of additive manufacturing intended for the production of tools or tooling components with reduced lead times as compared to conventional tooling. Rapid tooling may be produced directly by the additive manufacturing process or indirectly by producing patterns that are in turn used in a secondary process to produce the actual tools.

resolution*	Dimensions of the smallest part feature that can be controlled when built.
reverse engineering	A method of creating a digital representation from a physical object to define its shape, dimensions, and internal and external features.
selective laser melting	A generic name for metal powder bed fusion.
selective laser sintering	A trade name used by 3D Systems for the company's polymer powder bed fusion technology.
SFF	Solid freeform fabrication; another name for additive manufacturing.
sheet lamination*	Additive manufacturing process in which sheets of material are bonded to form a part.
SHL	Sheet lamination.
single-step process*	Additive manufacturing process in which parts are fabricated in a single operation where both geometric shape and material properties are achieved simultaneously.
SLA	Stereolithography apparatus.
SLM	Selective laser melting.
SLS	Selective laser sintering.
SMEs	Small- and medium-sized enterprises.
solid model	3D CAD representation somewhat analogous to using material, such as wood or plastic, to create a shape. Many solid-modeling software products use geometric primitives, such as cylinders and spheres, and features such as holes and slots, to construct 3D shapes. Solid models are preferred over surface models for additive manufacturing because they define a closed, "watertight" volume—a requirement of most additive manufacturing systems.
STEAM	Science, technology, engineering, art, and mathematics.
STEM	Science, technology, engineering, and mathematics; often used in association with education policy and curriculum development in schools to help improve competitiveness.
Stereolithography	See vat photopolymerization.

STL	File format for 3D model data used by machines to build physical parts. STL is the de facto standard interface for additive manufacturing systems. STL originated from the term stereolithography. The STL format uses triangular facets to approximate the shape of an object, listing the vertices, ordered by the right-hand rule, and unit normals of the triangles, and excludes CAD model attributes.
support*	Structure separate from the part geometry that is created to provide a base and anchor for the part during the building process.
surface model*	Mathematical or digital representation of an object as a set of planar or curved surfaces, or both, that can, but not necessarily have to represent a closed volume.
thermoplastic	A polymer that can be repeatedly melted, cooled, and solidified.
thermoset	A polymer that is permanently cured once polymerized.
tool, tooling	Mold, die, or another device used in various manufacturing processes such as plastic injection molding, thermoforming, blow molding, die casting, sheet metal stamping, hydroforming, forging, composite layup, machining, and assembly fixtures.
topological optimization	Same as topology optimization.
topology optimization	Use of mathematics to optimize the strength-to-weight ratio of a design. The approach minimizes the use for a given set of load and constraint conditions.
TPE	Thermoplastic elastomer; polymer that exhibits exceptional elastomeric properties.
TPU	Thermoplastic polyurethane; a class of polyurethane plastics (thermoplastic elastomers) that share properties of elasticity, transparency, and resistance to oil and grease.
triangulation	Method of inferring the location of a point on a surface by projecting light onto the surface and observing that light from a different angle or orientation.
vat photopolymerization*	Additive manufacturing process in which liquid photopolymer in a vat is selectively cured by light-activated polymerization.

virgin*	Condition of feedstock from a single manufacturing lot before being applied to the additive manufacturing process.
voxel	Volume element; objects and three-dimensional datasets can be divided into an array of discrete elements, called voxels, on a regular grid in three-dimensional space.
VPP	Vat photopolymerization.
WAAM	Wire-arc additive manufacturing

* denotes ISO/ASTM 52900 standard definition

Appendix B: System manufacturer matrix

T = thermoplastic	C = ceramic
X = composite	S = sand
P = photopolymer	B = biomaterials
M = metal	Z = other

Company	Sales From	MEX	MJT	BJT	VPP	SHL	PBF	DED
Argentina								
Trideo	2021	T						
Australia								
AmPro	2018						M	
Asiga	2012				P			
Aurora Labs	2017						M	
Gizmo 3D	2017				P			
SPEE3D	2017							M
Titomic	2020							M
Austria								
Cubicure	2017				P			
EVO-tech	2018	TX						
Genera	2021				P			
HAGE3D	2017	CMT						
Incus	2019				M			
Lithoz	2011				CB			
SBI	2020							M
UpNano	2019				P			
Venox Systems	2021	T						
W2P	2018				P			
Weirather	2018						T	
Belgium								
Colossus	2021	TX						
Brazil								
Alkimat	2015						CMT	
Omnitek	2018						M	
Romi	2020							M
Canada								
AON3D	2019	T						
Mosaic	2022	T						

Company	Sales From	MEX	MJT	BJT	VPP	SHL	PBF	DED
Nanogrande	2017						M	
Rapidia	2019	M						
China								
BMF	2018				CP			
Bright Laser Technologies (BLT)	2014						M	M
Chamlion Laser Technology	2020						M	
Coin Robotics	2021	T						
CoLiDo	2021	TX						
Dazzle	2021				P			
DediBot	2020	T			P		T	
EasyMFG	2021			MSX				
Eplus3D	2015				P		MST	
Farsoon	2012						MT	
FastForm	2019						M	
Fochif	2017	B			PC			
HBD (Hangbang 3D)	2017						M	
HeyGears	2020				P			
Huake 3D	2014						MTZ	
IBridger	2021	T						
IEMAI	2021	T						
INTAMSYS	2017	TX						
Kings 3D	2018				P		M	
Laseradd	2017						MT	
LiM Laser Technologies	2020						M	M
Longyuan	1996		P	S			M	
Magforms	2021				P			
Peopoly	2020				P			
TR	2017				P			
ProtoFab	2018				P		MT	
QBEAM	2017						M	
Raycham	2017						M	
Rayshape	2020				P			
Rxton	2018						M	M
Sailong Metal	2020						M	

Company	Sales From	MEX	MJT	BJT	VPP	SHL	PBF	DED
Shanghai Digital Manufacturing	2021	T			P			
Shining 3D	2019				P			
Techgine	2018						M	
Tiertime	1996	TX						
TPM3D	2012						T	
UnionTech	2001				P			
WiiBoox	2018	T			P		M	
ZRapid Tech	2017						CMT	
Columbia								
Fused Form	2021	T						
Czech Republic								
TRILAB	2021	T						
Denmark								
Addifab	2018				P			
COBOD	2020	Z						
Finland								
miniFactory	2018	TX						
France								
3DCeram Sinto	2014				C			
AddUp	2017						M	M
Epeire3D	2022	T						
Julien	2021	T						
Lynxter	2021	TZ						
Microlight	2019				P			
Pollen	2021	MT						
Prodways	2010		Z		PXC		TX	M
VOLUMIC	2021	T						
Germany								
2oneLab	2021						M	
3D MicroPrint	2018						M	
3D-Mectronic	2020						CMT	
Aconity3D	2019							M
AIM3D	2021	MTX						
Alpha Laser	2020						M	
AMCM	2020						MT	
Apium	2015	TX						

Company	Sales From	MEX	MJT	BJT	VPP	SHL	PBF	DED
Arburg	2014	T	TZ					
BigRep	2013	TX						
Chiron Group	2020							M
CR-3D	2021	T						
DMG	2021				P			
dp polar	2021		P					
EOS	1990						MT	
Gerfertec	2019							M
GEWO Feinmechanik	2017	TX						
Impact Innovations	2018							M
innovatiQ	2021	TZ						
KraussMaffei	2022	T			P			
Kulzer	2021				P			
Kumovis	2019	TX						
Kurtz Ersa	2019						M	
Lunovu	2018							M
Multec	2022	MTX						
Multiphoton Optics	2021				P			
Nanoscribe	2008				P			
One Click Metal	2022							
Orion	2021	T						
Precitec	2020							M
PYOT Labs	2021	T						
Rapid Shape	2011				P			
SLM Solutions	2011						M	
Trumpf	2004						M	
voxeljet	2006			TSC			T	
Vulcantech	2019						M	
Walter Feist Systemtechnik	2021	T						
Yizumi	2019	TX						
Hungary								
Voxeltek	2014				P			
India								
Amace	2021						M	
BFW	2022							M
Deltasys	2020	TZ						

Company	Sales From	MEX	MJT	BJT	VPP	SHL	PBF	DED
Intech	2019						M	
Make3d	2021	T						
STPL	2021	T			P			
Iran								
Noura	2017						M	
Israel								
IO Tech	2021		MZ					
Massivit	2016	P						
Modix	2019	TX						
Nano Dimension	2016		PM					
Stratasys	1991	T	P		P		T	
Tritone	2020		CM					
XJet	2017		CM					
Italy								
3D4MEC	2018						M	
3ntr	2017	TX						
Breton	2021	T						
CMS	2022	T						
DWS	2006				P			
Gimax3D	2018	TX						
Mark One	2019	TX						
MeccatroniCore (MTC)*	2021	T						
Prima Additive	2018						M	M
Roboze	2017	TX						
Sharebot	2015	T			P		M	
Sisma	2014				P		M	
WASP	2017	TXZ						
Japan								
Aspect	2007						TX	
CMET	1992			S	P			
D-MEC	1989				P			
DMG Mori	2014						M	M
JEOL	2022						M	
Keyence	2012		P					
Matsuura	2012						M	
Mimaki	2017		p					

Company	Sales From	MEX	MJT	BJT	VPP	SHL	PBF	DED
Mutoh	2017	TX			P			
Roland	2014				P			
Latvia								
Mass Portal	2021	TX						
Luxembourg								
Anisoprint	2018	TX						
Netherlands								
Additive Industries	2015						M	
Admatec	2017				CM			
Atum 3D	2017				P			
Blackbelt	2020	T						
Builder	2017	T						
byFlow	2021	Z						
CEAD	2020	TX						
Concr3de	2021			CMX				
CyBe Construction	2017	Z						
FELIXPrinters	2019	BT						
Luxexcel (Meta)	2018				PZ			
MX3D	2021							M
Opiliones	2020	TX						
Ramlab	2018							M
Tractus 3D	2020	TX						
Poland								
3DGence	2018	T						
Omni3D	2017	TX						
Sinterit	2015						T	
SondaSys	2018						T	
Sygnis	2020	BTZ						
UBOT 3D	2019	TX						
Vshaper	2017	T						
Zortrax	2018	TX			P			
Portugal								
Addcreative	2019						M	
Romania								
Symme 3D	2022	TB						
Russia								
Red Rock 3D	2020						T	

Company	Sales From	MEX	MJT	BJT	VPP	SHL	PBF	DED
Rusatom	2020						MT	
Ruselectronics	2021						M	
Total Z	2017	TX					T	
Singapore								
Structo	2015				P			
South Africa								
Aditiv Solutions	2021						M	
Amnova Tech	2020	T						
South Korea								
3DControls	2022				C			
AON 3D (Korea)	2021				C			
Carima	2009				CP			
Cubicon	2020	T			P			
CY Autotech	2020						M	
InssTek	2011							M
KLabs	2018	T		CMZ				
Lincsolution	2018	T			P			
Lugolabs	2022	TX						
Merain	2017						M	
Moment	2019	TX						
Sindoh	2019	TX			P			
Solid Freeform Systems	2020			S			M	
TPC Mechatronics	2022	B			PC			
Trend Seoul	2017	T						
Veltz	2022				P			
Winforsys	2022						M	
Spain								
CNC Barcenas	2018	TX						
Dynamical3D	2017	TX						
Meltio	2019	M						M
Moso 3D	2022	T						
Natural Robotics	2019	T					T	
SamyLabs	2018						M	
Tumaker	2021	T						
Sweden								
Digital Metal	2016			M				

Company	Sales From	MEX	MJT	BJT	VPP	SHL	PBF	DED
Fluicell	2021	B						
The Industry	2022	TX						
ZYYX Labs	2021	TX						
Switzerland								
Nematx	2022	T						
Sintratec	2017						T	
Taiwan								
MicroJet	2017			CX				
Phrozen					P			
Tongtai	2020						M	
XYZprinting	2017	T		X			T	
Turkey								
3bfab	2017				P			
Ermaksan	2019						M	
Loop 3D	2019	CTX						
Novafab	2018				P			
Sinterjet	2022			M				
U.S.								
3D Platform	2017	TX						
3D Systems	1988		PZ	X	P		MT	
3DXTECH	2021	T						
Addere	2020							M
Advanced Solutions	2020	B						
Allevi	2020	B						
Apis Cor	2021	Z						
Azul3D	2021				P			
B9Creations	2020				P			
Brinter	2022	B						
Carbon	2017				P			
Cosine Additive	2016	TX						
Desktop Metal	2017	TMX		M				
Diabase	2019	TX						
Essentium	2020	TX						
ETEC	2002				BCT			
Evolve Additive	2020					T		
ExOne	2001			MSC				
Fabrisonic	2011					M		

Company	Sales From	MEX	MJT	BJT	VPP	SHL	PBF	DED
Formalloy	2018							M
Formlabs	2017				P		T	
Fortify	2020				PX			
Fusion3	2021	T						
GE Additive	2018			M			M	
HP	2016			M			T	
Hybrid Manufacturing	2020							M
Hyrel 3D	2020	TZ						
IC3D	2021	T						
Impossible Objects	2018					X		
Ingersoll Machine Tools	2022	CTX						
JuggerBot 3D	2019	TX						
Laser Photonics	2020						M	
Loci Robotics	2022	T						
LuxCreo	2021				P			
Markforged	2014	TXM						
Millebot	2021	MTZ						
Nexa3D	2017				P		T	
nScrypt	2017	BT						
Open Additive	2019						M	
Optomec	1998		Z					M
Orbital Composites	2021	X						
re:3D	2017	TX						
RPM Innovations	2014							M
Sciaky	2011							M
Sodick	2014						M	
Solidscape	1994		PZ					
SprintRay	2020				P			
Stacker	2018	TX						
SunP Biotech	2018	B						
Surgino	2022							M
Tethon 3D	2021				C			
Thermwood	2017	TX						
Titan Robotics	2015	TX						
Tytus3D	2019						M	
UNIZ	2020				P			

Company	Sales From	MEX	MJT	BJT	VPP	SHL	PBF	DED
Velo3D	2018						M	
Xact Metal	2018						M	
UK								
Photocentric	2018				P			
Renishaw	2011						M	
RPS	2019				P			
WAAM3D	2021							M
Wayland Additive	2021						M	
Ukraine								
Additive Laser Technology	2020						M	
(xBeam 3D)	2017							M

Appendix C: Metal AM comparison matrix

Several pages of tables compare many details of multiple metal AM processes. Go to wohlersassociates.com/metalam2023.pdf to view the information. These pages are exclusive and not published elsewhere. All company information and product specification data are subject to change.

Appendix D: 3D scanning systems

Several pages of tables compare the technology, work volume, accuracy, and speed of 3D scanning systems from around the world. Go to wohlersassociates.com/scan2023.pdf to view the information. These pages are exclusive and not published elsewhere. All company information and product specification data are subject to change.

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