ENPM 692
MANUFACTURING AND AUTOMATION

ADDITIVE MANUFACTURING

Time: Wednesdays 7:00pm - 9:40pm
Location: JMP 2222

Dr. Mahesh Mani, PhD
Email: mmani@umd.edu

Recap

- Course expectations
- Manufacturing classifications
- Industrial automation
  - Video
  - Automation in production systems
  - Elements of automation
  - Levels of automation

Economically disruptive technologies

Mobile Internet	Increasingly inexpensive and capable mobile computing devices and Internet connectivity
Automation of knowledge work	Intelligent software systems that can perform knowledge work tasks involving unstructured commands and subtle judgments
The Internet of Things	Networks of low-cost sensors and actuators for data collection, monitoring, decision making, and process optimization
Cloud technology	Use of computer hardware and software resources delivered over a network or the Internet, often as a service
Advanced robotics	Increasingly capable robots with enhanced senses, dexterity, and intelligence used to automate tasks or augment humans
Autonomous and near-autonomous vehicles	Vehicles that can navigate and operate with reduced or no human intervention

Next-generation genomics	Fast, low-cost gene sequencing, advanced big data analytics, and synthetic biology ("writing" DNA)
Energy storage	Devices or systems that store energy for later use, including batteries
3D printing	Additive manufacturing techniques to create objects by printing layers of material based on digital models
Advanced materials	Materials designed to have superior characteristics (e.g., strength, weight, conductivity) or functionality
Advanced oil and gas exploration and recovery	Exploration and recovery techniques that make extraction of unconventional oil and gas economical
Renewable energy	Generation of electricity from renewable sources with reduced harmful climate impact

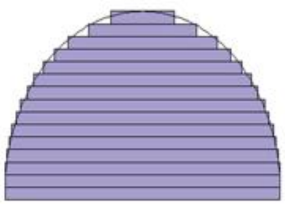
Source: http://www.mckinsey.com/insights/business_technology/disruptive_technologies

Lectures

Lecture 1	1/29/2025	Introduction Lecture
Lecture 2	2/5/2025	Additive Manufacturing- technologies
Lecture 3	2/12/2025	Additive Manufacturing- capabilities and applications
Lecture 4	2/19/2025	Sustainable Manufacturing –Overview
Lecture 5	2/26/2025	Sustainable Manufacturing Practicality
Lecture 6	3/5/2025	Industrial Robotics
Lecture 7	3/12/2025	Guest Lecture
Spring Break	3/19/2025	No Lecture-Spring Break
Lecture 8	3/26/2025	Manufacturing Simulation
Lecture 9	4/2/2025	Digital Manufacturing
Lecture 10	4/8/2025	Network Centric Manufacturing
Lecture 11	4/16/2025	Network Centric Manufacturing
Lecture 12	4/23/2025	Guest Lecture
Lecture 13	4/30/2025	Smart Manufacturing Platforms
Lecture 14	5/7/2025	Final - Project Presentations
Lecture 15	5/14/2025	Final - Project Presentations

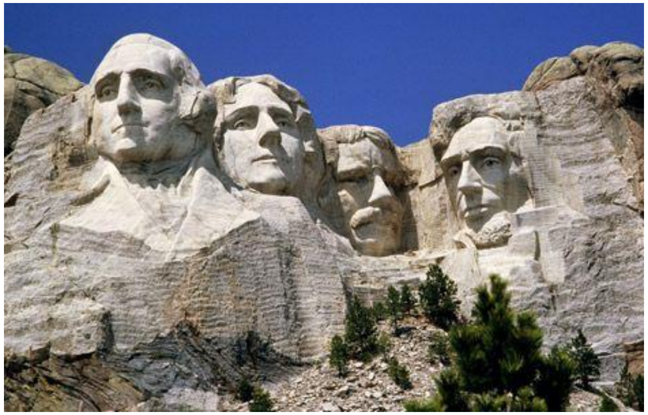
What is Additive Manufacturing (AM)?

- Additive process—layer by layer



Traditional manufacturing — subtractive process

- Starts with a bulk piece of material and
- Gradually remove material



Definition

- Additive manufacturing is the official industry standard term (ASTM F2792) for all applications of the technology.
- It is defined as the process of joining materials to make objects from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing methodologies.
- Synonyms are additive fabrication, additive processes, additive techniques, additive layer manufacturing, layer manufacturing, freeform fabrication, 3D printing.

Generic AM Process

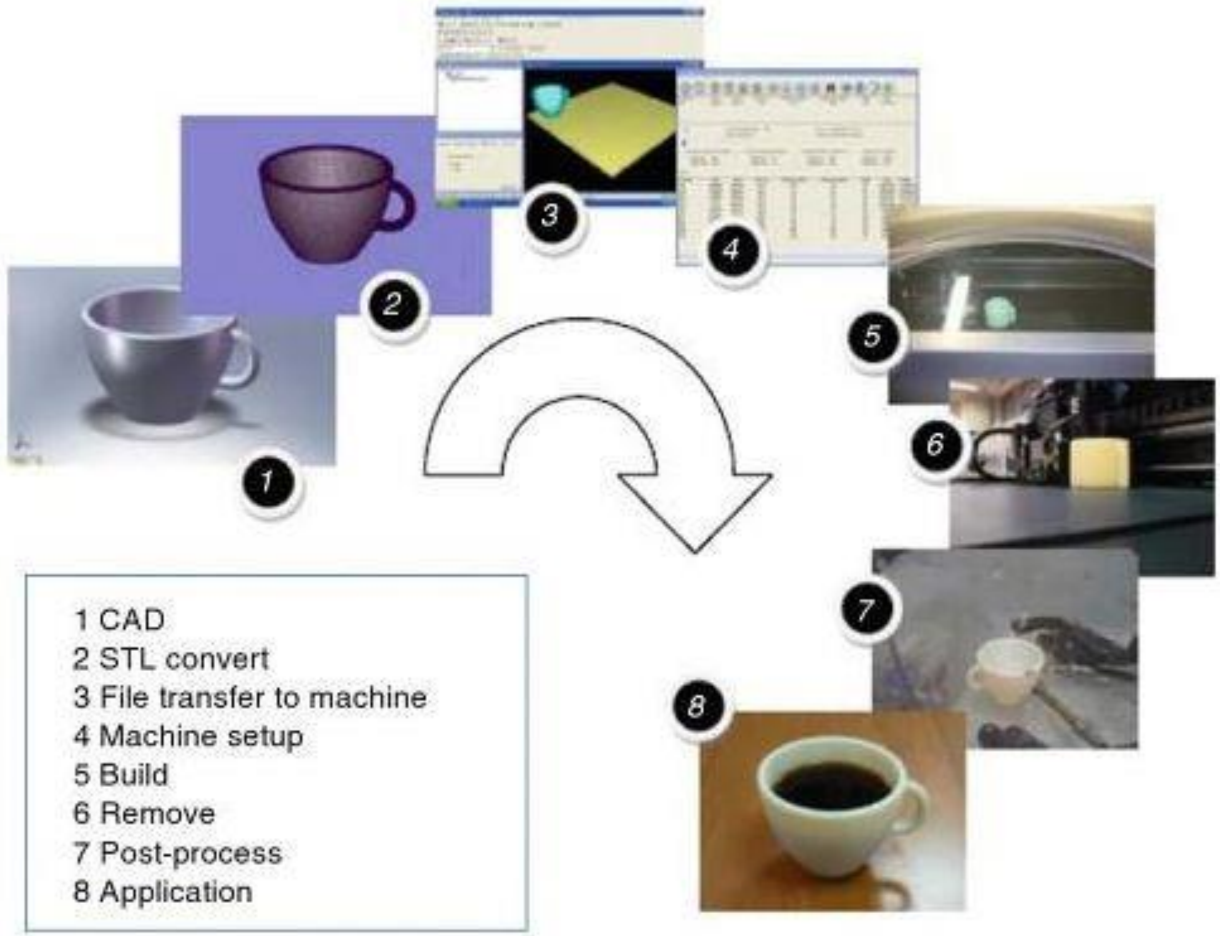
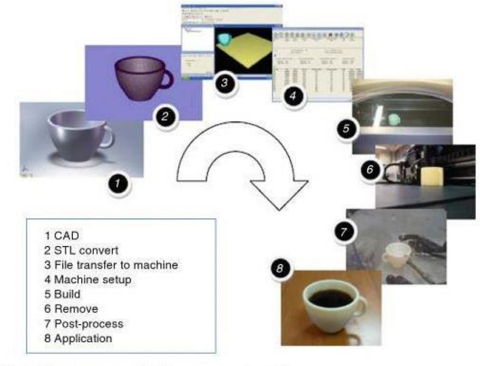


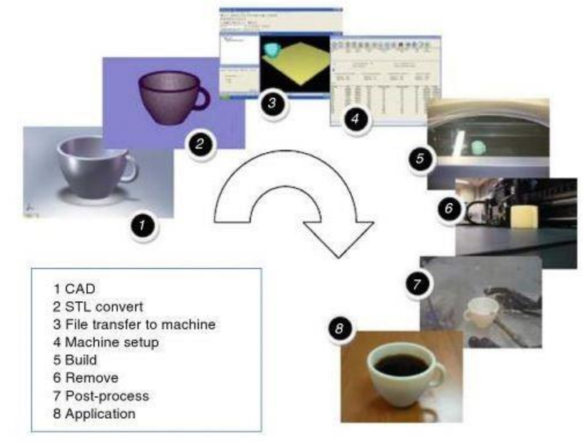
Figure 1.2 Generic process of CAD to part, showing all 8 stages, Gibson et al.

Steps 1-4



- Step 1: CAD
  - All AM parts start from a software model - 3D solid or surface representation.
  - Reverse engineering equipment (e.g., laser scanning) can also be used to create this representation.
- Step 2: Conversion to STL
  - A de facto standard, and acceptable in every CAD.
  - STL describes the external closed surfaces of the original CAD model and forms the basis for calculation of the slices.
- Step 3: Transfer to AM Machine and STL File Manipulation
  - STL file transferred to the AM machine.
  - Manipulation of the file so that it is the correct size, position, and orientation for building.
- Step 4: Machine Setup
  - Build parameters like material constraints, energy source, layer thickness, timings, etc.

Steps 5-8



- Step 5: Build
  - An automated process and the machine can largely carry on without supervision.
- Step 6: Removal
  - Once build, the parts must be removed.
  - Machine dependent interaction for removal.
- Step 7: Post processing
  - Additional cleaning up before they are ready for use.
  - Supporting features that must be removed.
- Step 8: Application
  - Parts may now be ready to be used.
  - Some parts require additional treatment before they are acceptable for use.

General Integration of an AM machine

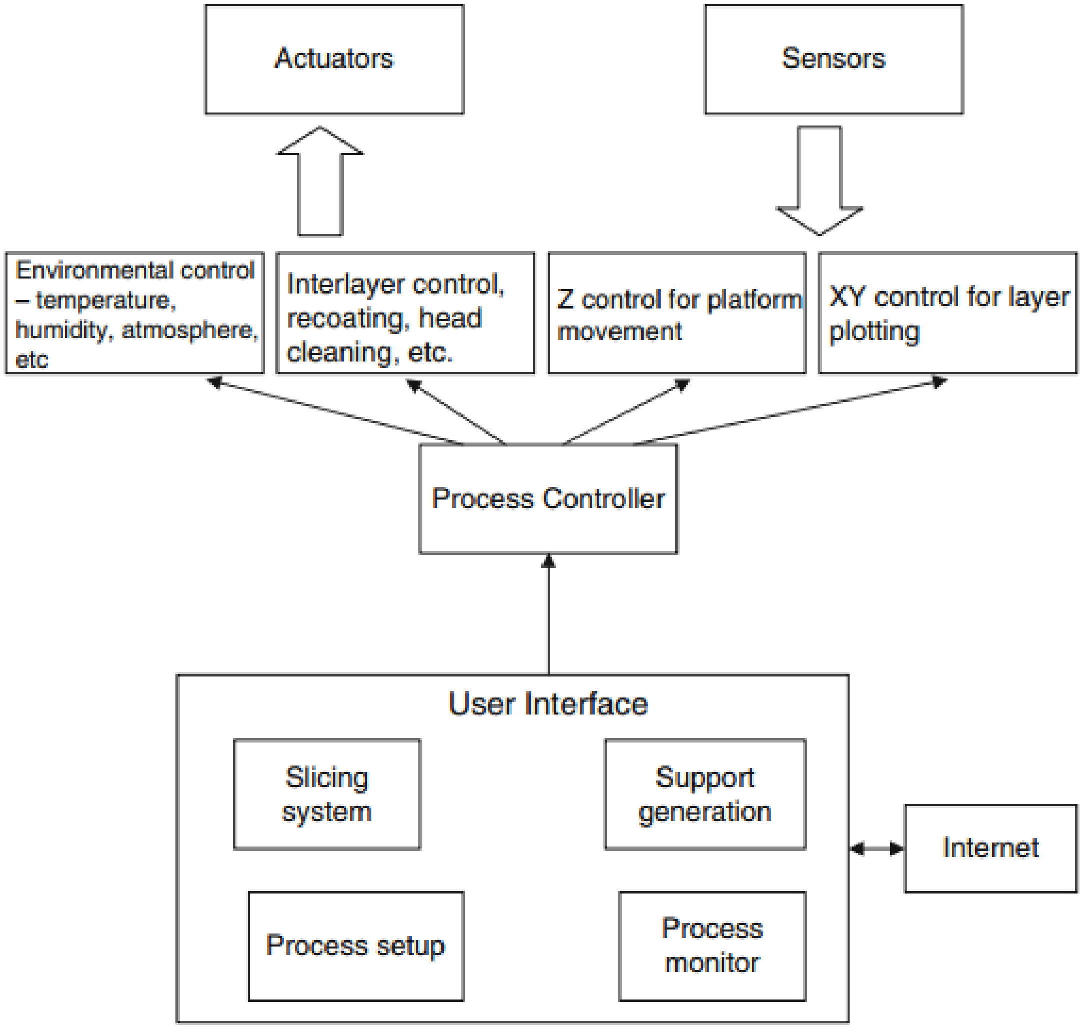


Fig. 2.1 General integration of an AM machine

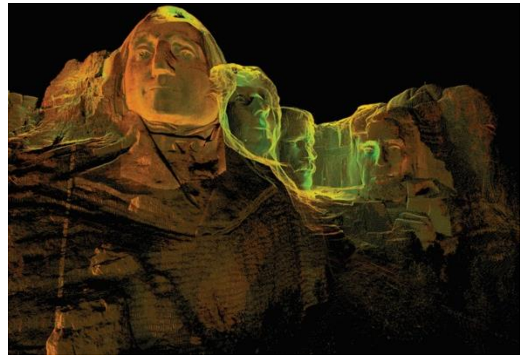
Video Demonstration

Source: Youtube

Video Demonstration

Example: Mount Rushmore

Setup

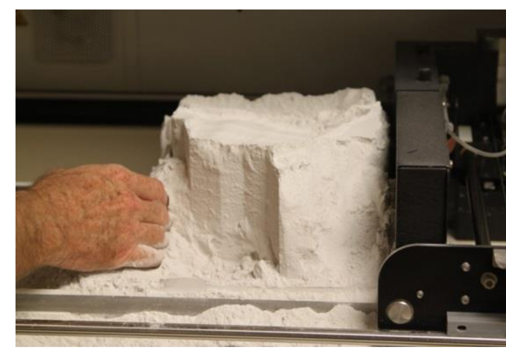


Scan

CAD Model

Finished Product

Post Processing



Print

Source: WWW, CyArk

More Information on the example

- **2010 Digital Scanning Project**

  http://web.archive.org/web/20120607003908/http://www.nps.gov:80/moru/parknews/2010-digital-scanning-project.htm

- **Scanning Mount Rushmore**
  https://www.youtube.com/watch?v=fDa_zvF9nyY

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Mount Rushmore
National Memorial
South Dakota

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2010 Digital Scanning Project

Mount Rushmore National Memorial is in the process of a ground-breaking three-dimensional laser scanning project. Memorial staff will be using the latest laser scanning technology to create a highly detailed record of the sculpture and other historic resources at the park.

NPS PHOTO BY AMY BRACEWELL
Maureen Young from Historic Scotland preps one of the laser scanning stations to begin scanning Borglum's model in the Sculptor's Studio

The value of the 3-D scanning provides realistic digital information of the site and has applications to provide innovative and interactive public interpretation, education, research and security programs. In the event of an incident resulting in the damage of the sculpture, the data would provide the information necessary to accurately replicate carved surfaces. The digital data will also give the NPS the ability to develop a very realistic interactive model for Mount Rushmore for education and interpretation including potential "virtual tours" of the memorial, as well as the entire site.

Scanning Team and Partners
The scanning team consists of members of the Memorial's technical ropes team, scanning specialists from the Kacyra Family Foundation and their project CyArk, Historic Scotland, and the Glasgow School of Art, as well as local technical consulting staff from Respec Engineers, Inc., Wyss and Associates, Inc., and the South Dakota School of Mines and Technology.

The scanning of Mount Rushmore is also a part of a scanning project called the Scottish 10 by Historic Scotland and the Glasgow School of Art. The goal of the Scottish 10 is to scan the 5 World Heritage Sites in Scotland and 5 international heritage sites, with Mount Rushmore as the first international site.

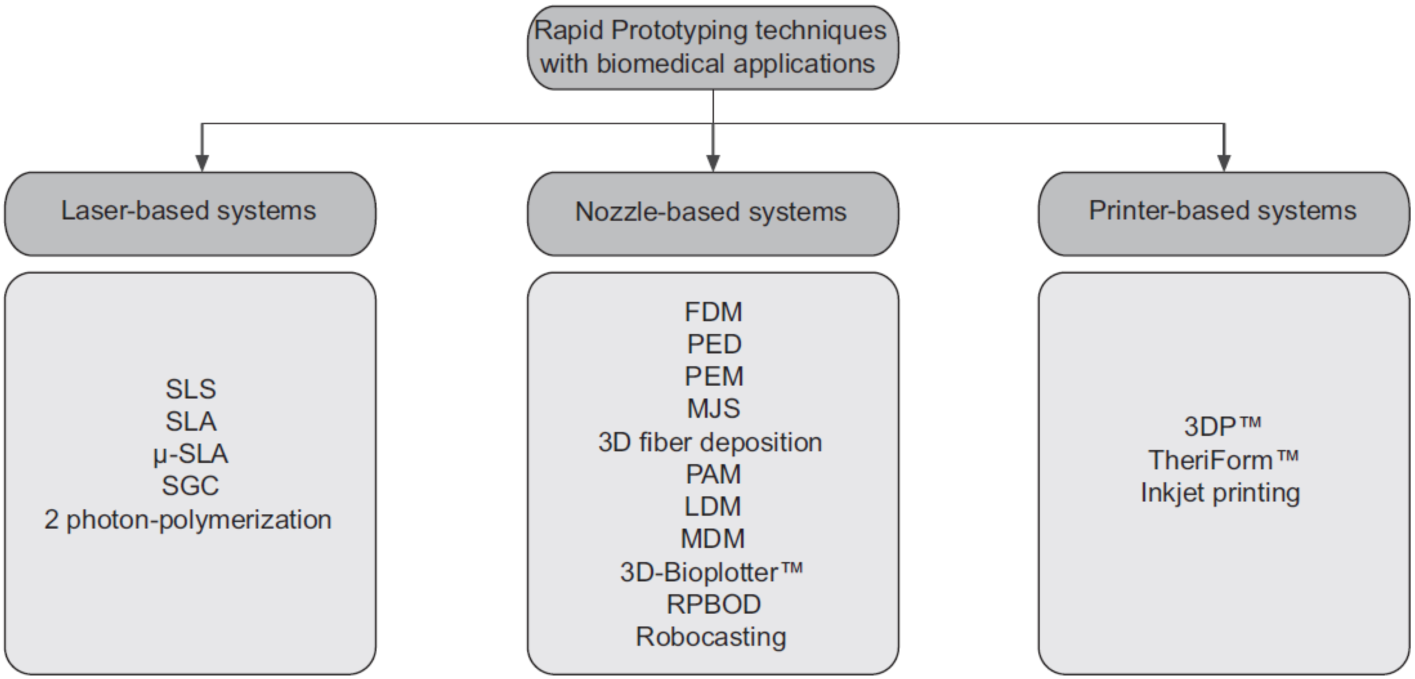
All of these projects, including the scanning of Mount Rushmore, are among the CyArk 500 initiative which is a global effort to digitally preserve 500 of the world's heritage sites.

Taxonomy of AM Processes

Many different classifications of AM technologies:

- **System technology**
  - Laser, nozzle, printer.
- **State of material**
  - Liquid, powder, solid.
- **Material based**
  - Polymers, metals, ceramics, composites.

Different Classifications



Source: *A review of trends and limitations in hydrogel-rapid prototyping for tissue engineering*

Fig. 2. Classification of RP techniques with biomedical applications into laser-, n

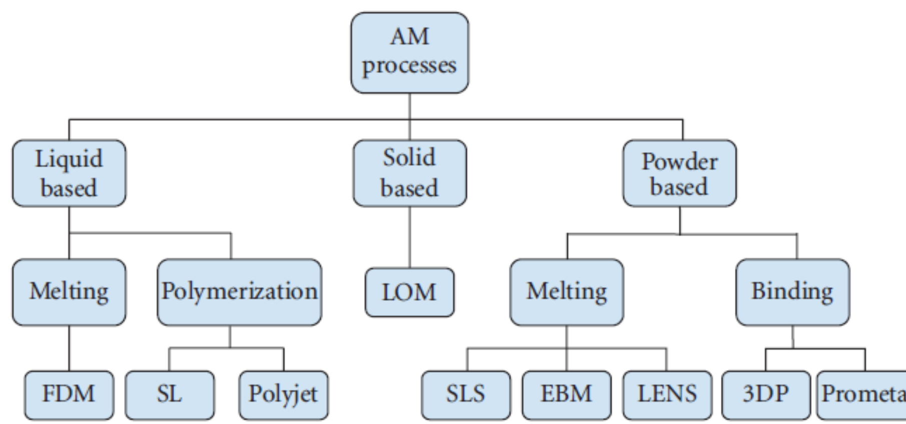
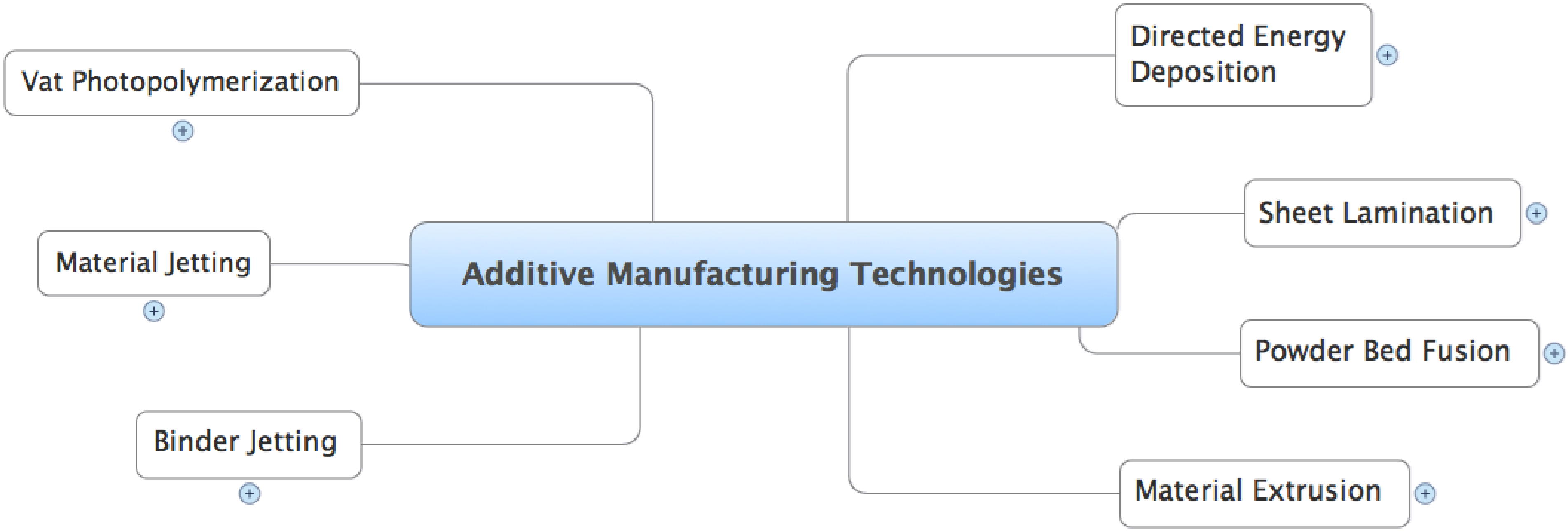


FIGURE 3: Three-dimensional printing processes. Adapted from [11].

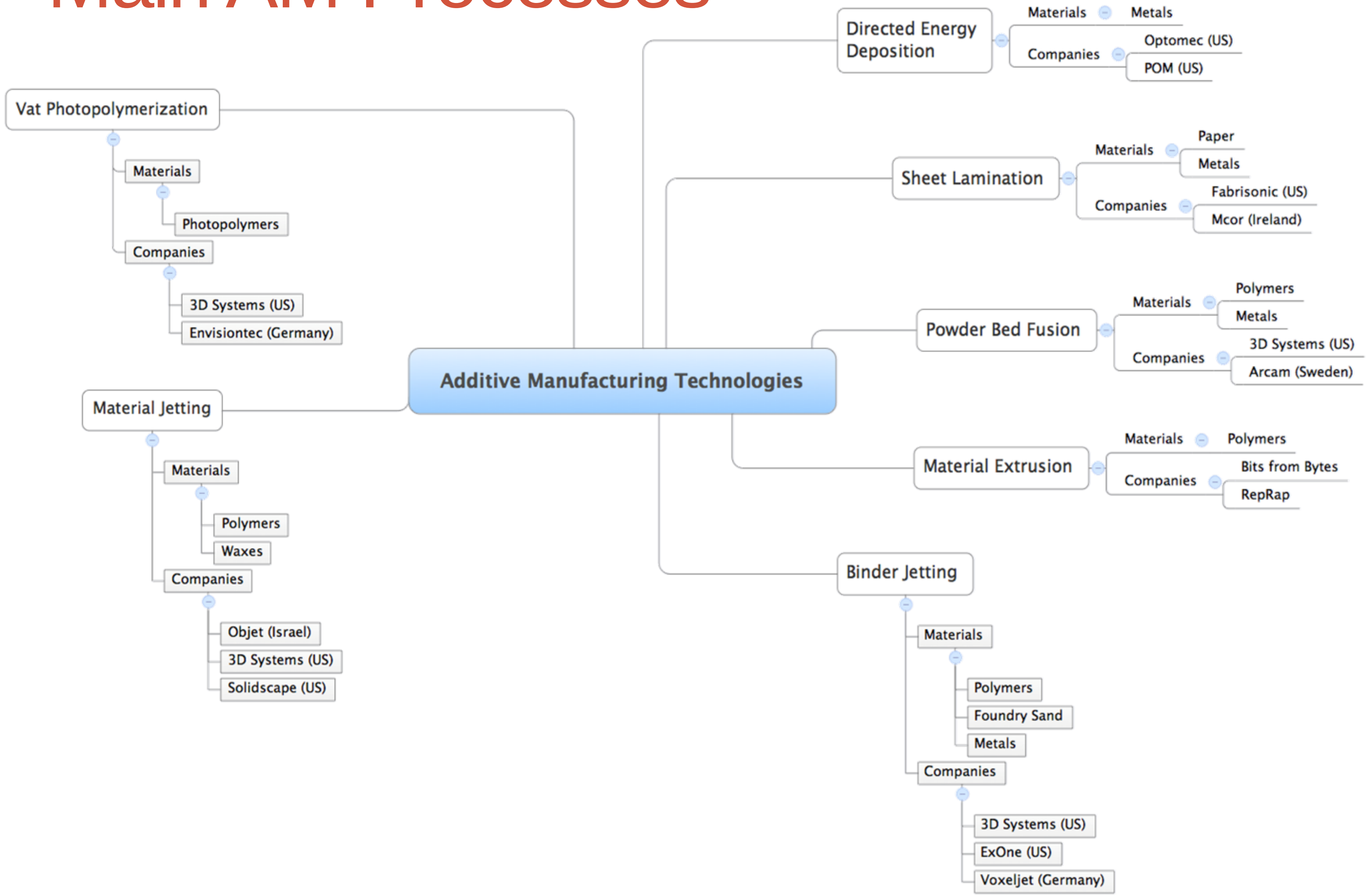
Source: A Review of Additive Manufacturing

ASTM F42 AM Classification



http://www.astm.org/COMMITTEE/F42.htm

Main AM Processes



Definitions

- Binder Jetting: This process uses liquid bonding agent deposited using an inkjet-print head to join powder materials in a powder bed.
- Directed Energy Deposition: This process utilizes thermal energy, typically from a laser, to fuse materials by melting them as they are deposited.
- Material Extrusion: These machines push material, typically a thermoplastic filament, through a nozzle onto a platform that moves in horizontal and vertical directions.
- Material Jetting: This process, typically, utilizes a moving inkjet-print head to deposit material across a build area.
- Powder Bed Fusion: This process uses thermal energy from a laser or electron beam to selectively fuse powder in a powder bed.
- Sheet Lamination: This process uses sheets of material bonded to form a three-dimensional object.
- Vat Photopolymerization: These machines selectively cure a liquid photopolymer in a vat using light.

Vat Photopolymerization

- Model is constructed layer by layer using a vat of liquid photopolymer
- An ultraviolet (UV) light is used to cure or harden the resin where required, whilst a platform moves the object being made downwards after each new layer is cured.

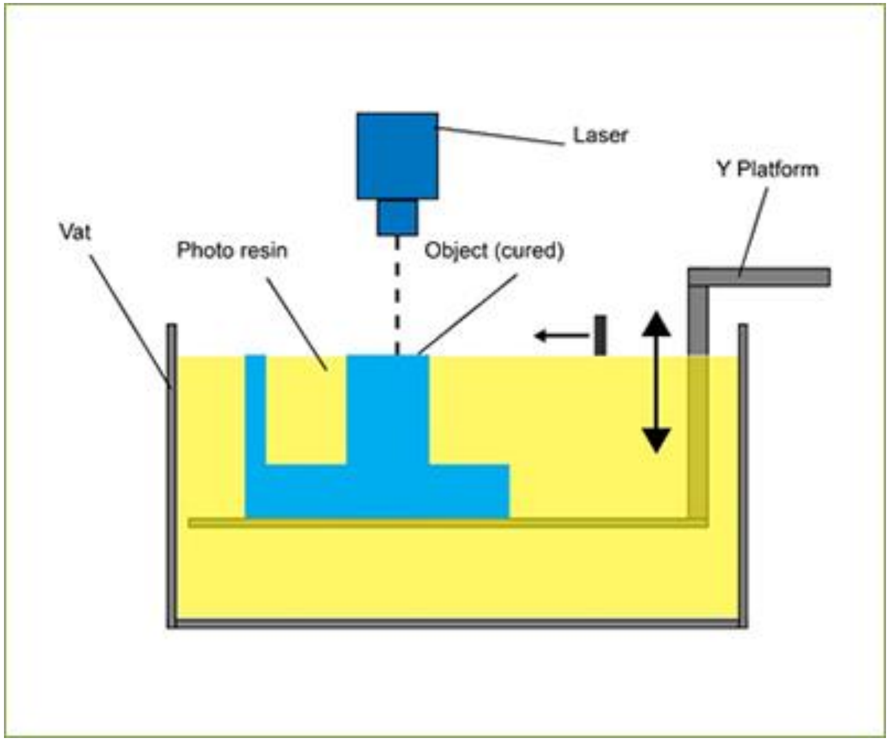
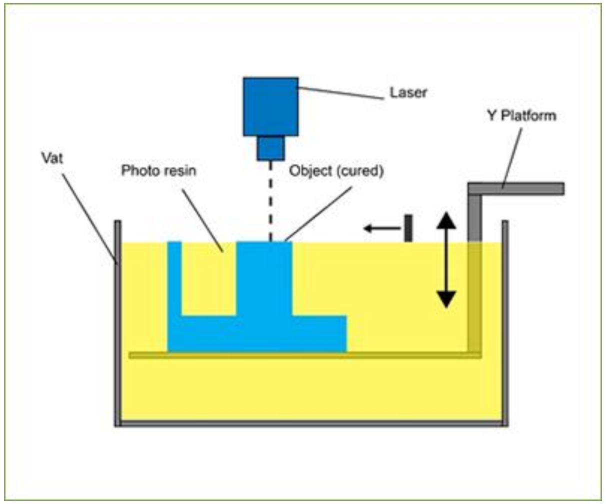


Figure: Photopolymerization Process

Picture Source: http://www.lboro.ac.uk/

Vat Photopolymerization



Advantages

- Good accuracy and good finish.
- Relatively quick process

Materials:

The Vat polymerization process uses Plastics and Polymers.

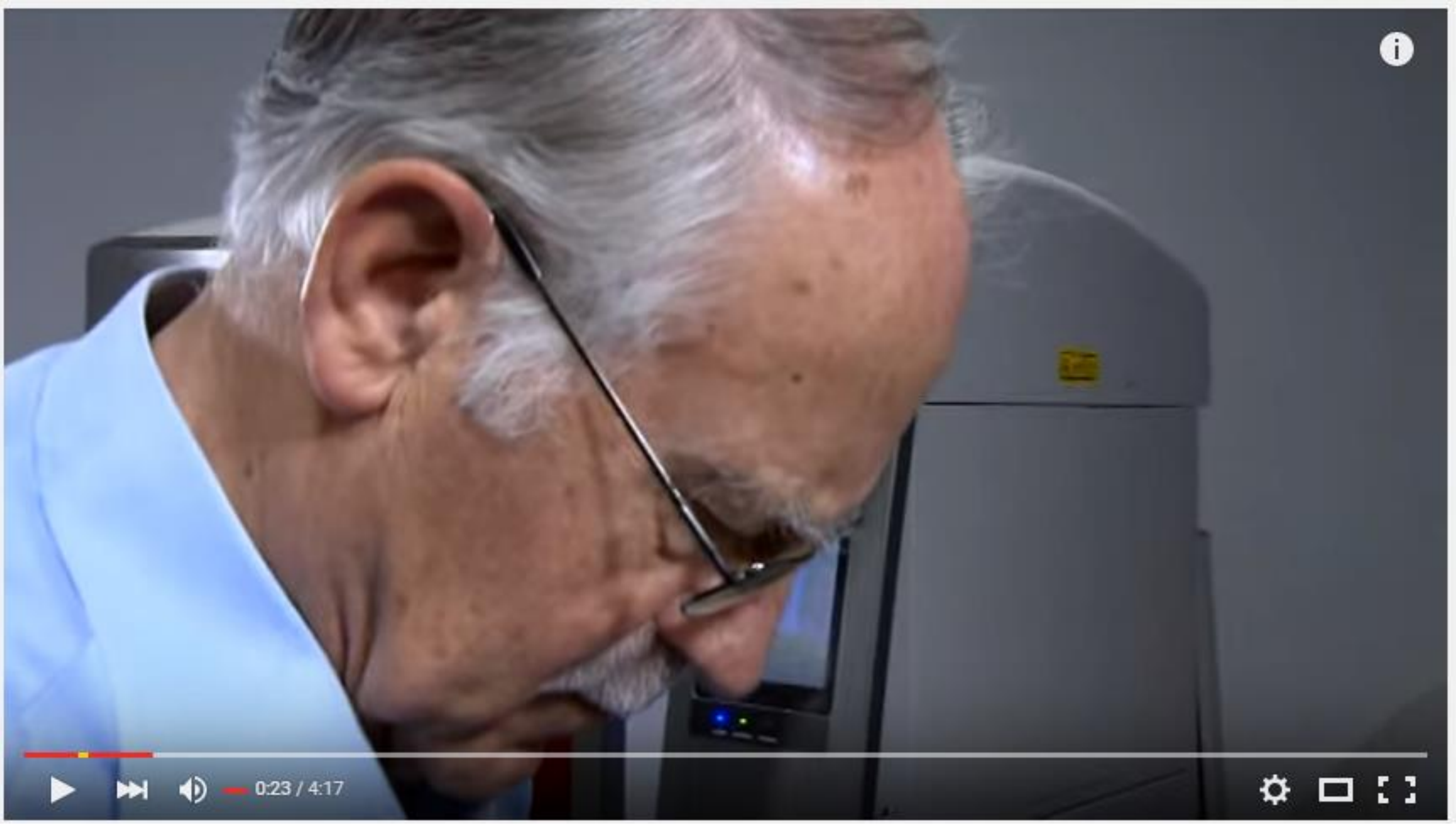
Polymers: UV-curable Photopolymer resin

Resins: Visijet range (3D systems)

Disadvantages:

- Relatively expensive.
- Lengthy post processing time and removal from resin.
- Limited material use of photo-resins.
- Often requires support structures and post curing for parts to be strong enough for structural use.

Vat Photopolymerization



https://www.youtube.com/watch?v=3uYsviZ8Cuo

Material Jetting Process

- The print head is positioned above build platform.
- Droplets of material are deposited from the print head onto surface where required.
- Droplets of material solidify and make up the first layer.
- Further layers are built up as before on top of the previous.
- Layers are allowed to cool and harden or are cured by UV light. Post processing includes removal of support material.

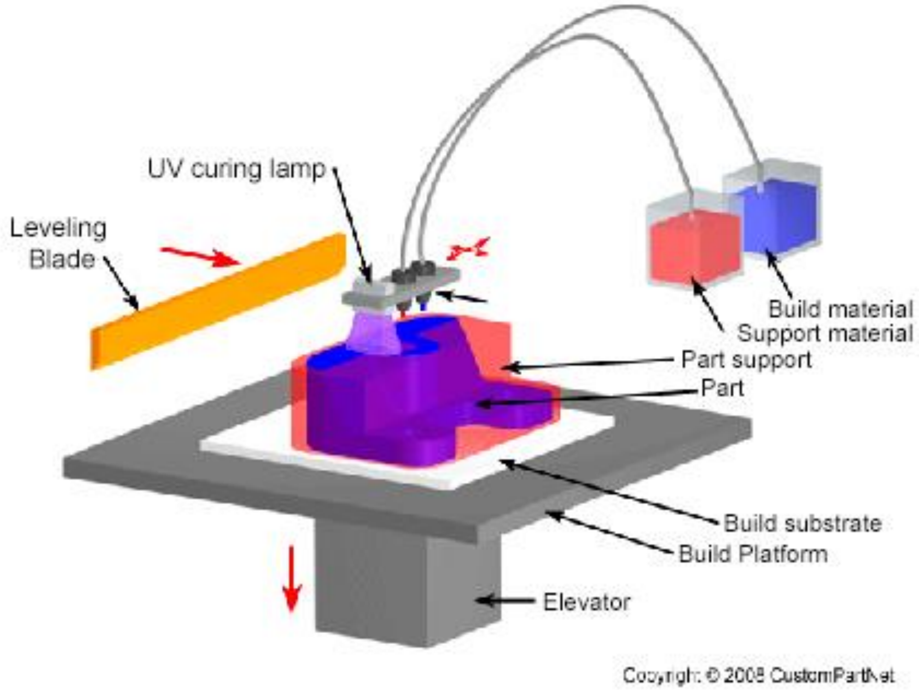
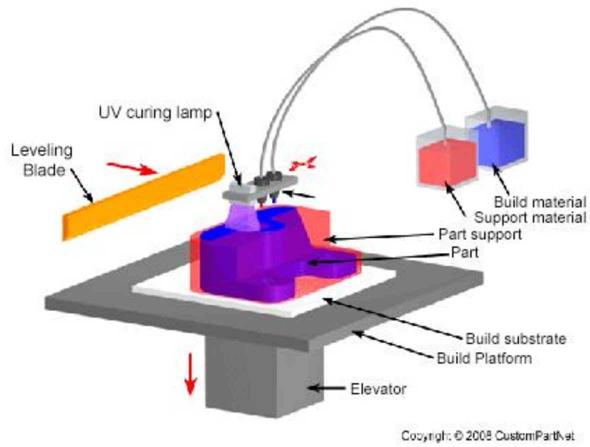


Figure: Material Jetting Process

Picture Source: http://www.lboro.ac.uk/

Material Jetting Process



Materials:

The material jetting process uses polymers and plastics.

Polymers: Polypropylene, HDPE, PS, PMMA, PC, ABS, HIPS, etc.

Advantages

- The process benefits from a high accuracy of deposition of droplets and therefore low waste
- The process allows for multiple material parts and colors under one process

Disadvantages:

- Support material is often required
- A high accuracy can be achieved but materials are limited and only polymers and waxes can be used

Picture Source: http://www.lboro.ac.uk/

Material Jetting Process

https://www.youtube.com/watch?v=Ahfepwpn-00

Directed Energy Deposition

- A 4 or 5 axis arm with a nozzle moves around a fixed object.
- Material is deposited from the nozzle onto existing surfaces of the object.
- Material is either provided in wire or powder form.
- Material is melted using a laser, electron beam or plasma arc upon deposition.
- Further material is added layer by layer and solidifies, creating or repairing new material features on the existing object.

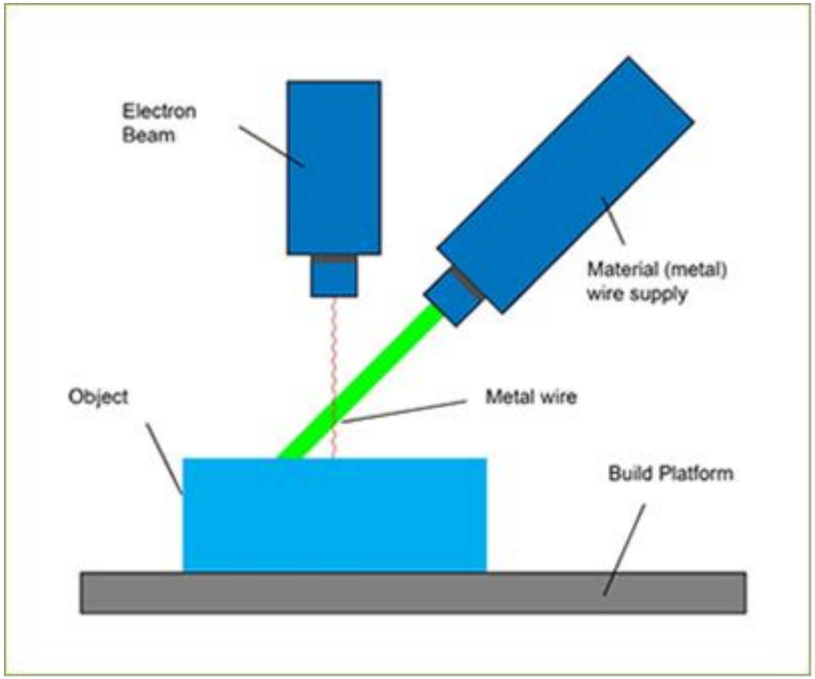
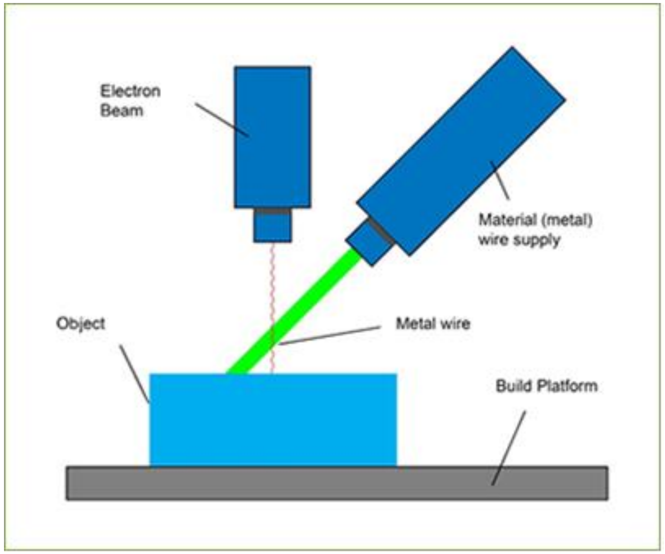


Figure: Directed Energy Deposition

Picture Source: http://www.lboro.ac.uk/

Directed Energy Deposition



Materials:
Metals: Cobalt Chrome, Titanium

Advantages

- Ability to control the grain structure to a high degree, which lends the process to repair work of high quality, functional parts.
- A balance is needed between surface quality and speed, although with repair applications, speed can often be sacrificed for a high accuracy and a pre- determined microstructure .

Disadvantages:

- Limited material use.
- Fusion processes require more research to further advance the process.
- Expensive post-processing.

Directed Energy Deposition

https://www.youtube.com/watch?v=d2foaRi4nxM

Sheet Lamination

- The material is positioned in place on the cutting bed.
- The material is bonded in place, over the previous layer, using the adhesive.
- The required shape is then cut from the layer, by laser or knife.
- The next layer is added.
- Steps two and three can be reversed and alternatively, the material can be cut before being positioned and bonded.

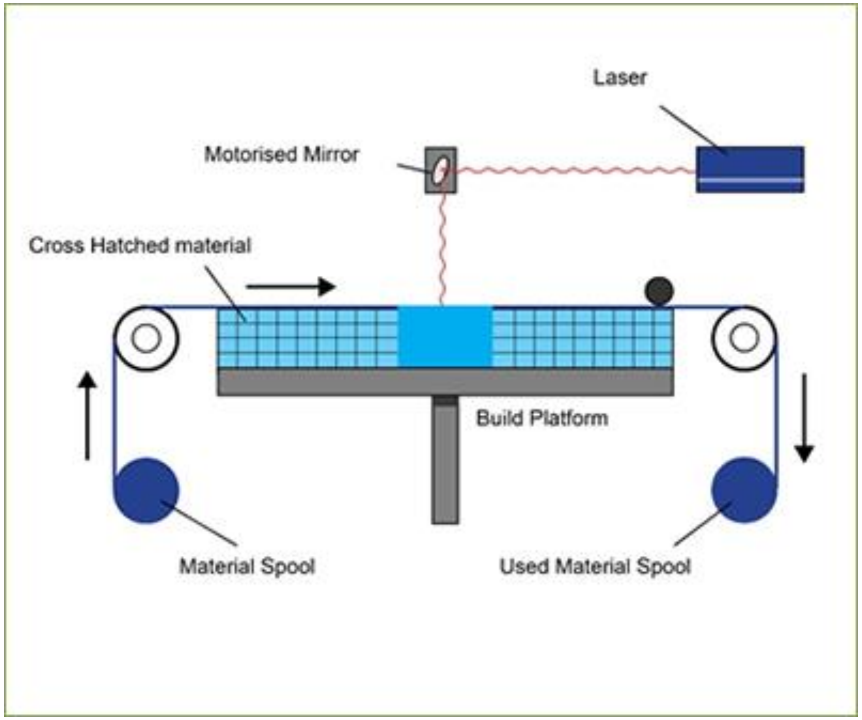
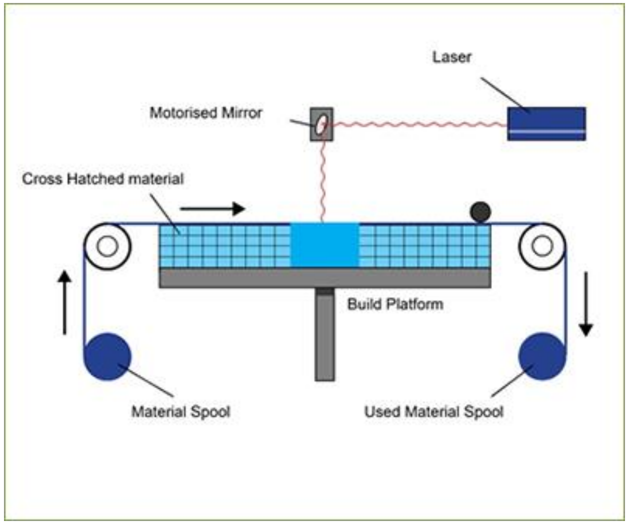


Figure: Sheet Lamination process

Picture Source: http://www.lboro.ac.uk/

Sheet Lamination



Advantages:

- Benefits include speed, low cost, ease of material handling, but the strength and integrity of models is reliant on the adhesive used.
- Cutting can be very fast due to the cutting route only being that of the shape outline, not the entire cross-sectional area.

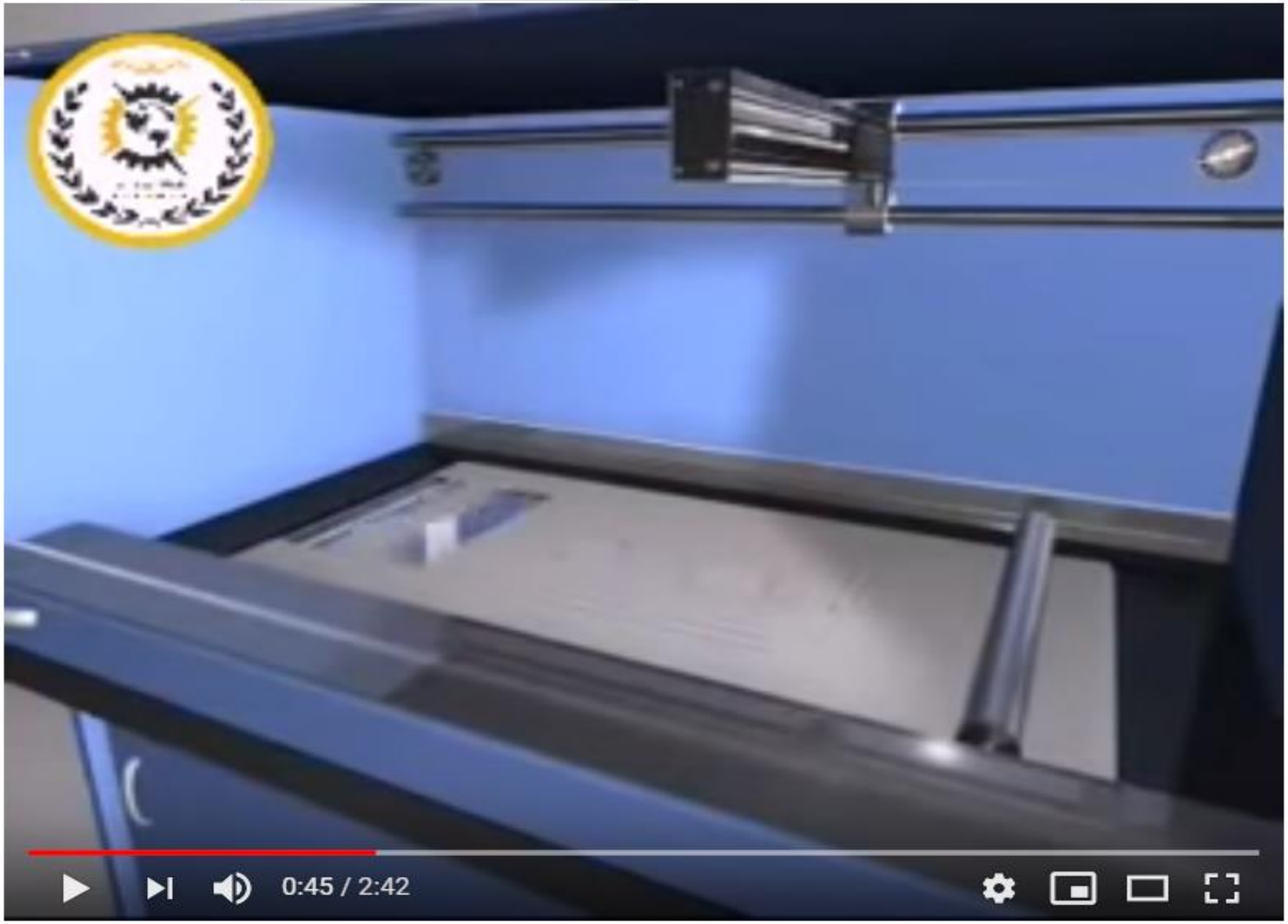
Materials:

Effectively any sheet material capable of being rolled. Paper, plastic and some sheet metals.

Disadvantages:

- Finishes can vary depending on paper or plastic material but may require post processing to achieve desired effect
- Limited material use
- Fusion processes require more research to further advance the process into a more mainstream positioning

Sheet Lamination



https://www.youtube.com/watch?v=oiSzUSeASAI

Powder Bed Fusion

- Layer, typically 0.1mm thick of material is spread over the build platform.
- Laser fuses the first layer or first cross section of the model.
- New layer of powder is spread across the previous layer using a roller.
- Further layers or cross sections are fused and added.
- The process repeats until the entire model is created. Loose, unfused powder is remains in position but is removed during post processing.

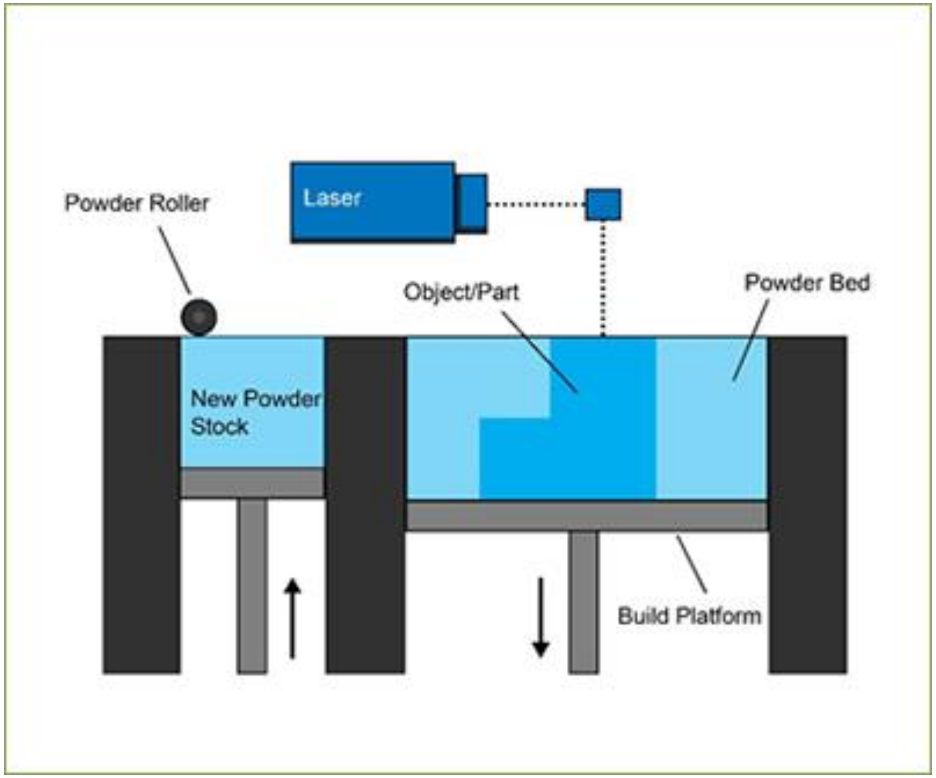
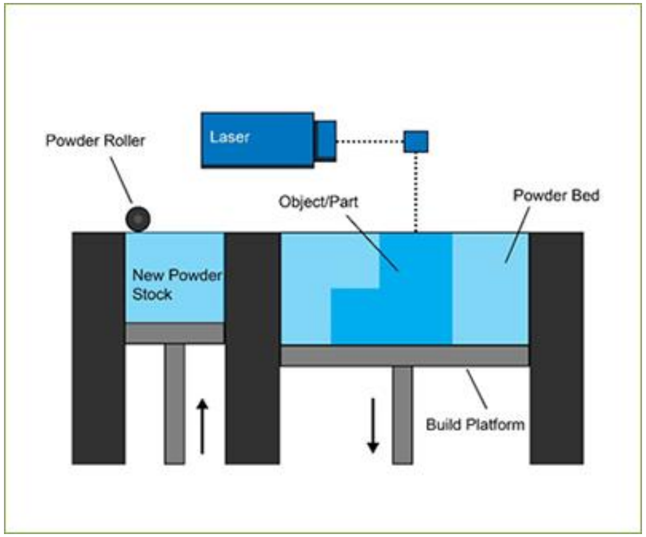


Figure: Powder Bed Fusion process

Picture Source: http://www.lboro.ac.uk/

Powder Bed Fusion



Materials:
Metals and Polymers
SLS: Nylon
DMLS, SLS, SLM: Stainless Steel, Titanium, Aluminum, Cobalt Chrome, Steel
EBM: Titanium, Cobalt Chrome, Stainless Steel, Aluminum and Copper

Advantages:

- Relatively inexpensive.
- Suitable for visual models and prototypes.
- Ability to integrate technology into small scale, office sized machine.
- Powder acts as an integrated support structure.
- Large range of material options.

Disadvantages:

- Relatively slow speed
- Lack of structural properties in materials
- Size limitations
- High power usage
- Finish is dependent on powder grain size

Powder Bed Fusion

https://www.youtube.com/watch?v=9E5MfBAV_tA

Material Extrusion

- First layer is built as nozzle deposits material where required onto the cross-sectional area of first object slice.
- The following layers are added on top of previous layers.
- Layers are fused together upon deposition as the material is in a melted state.

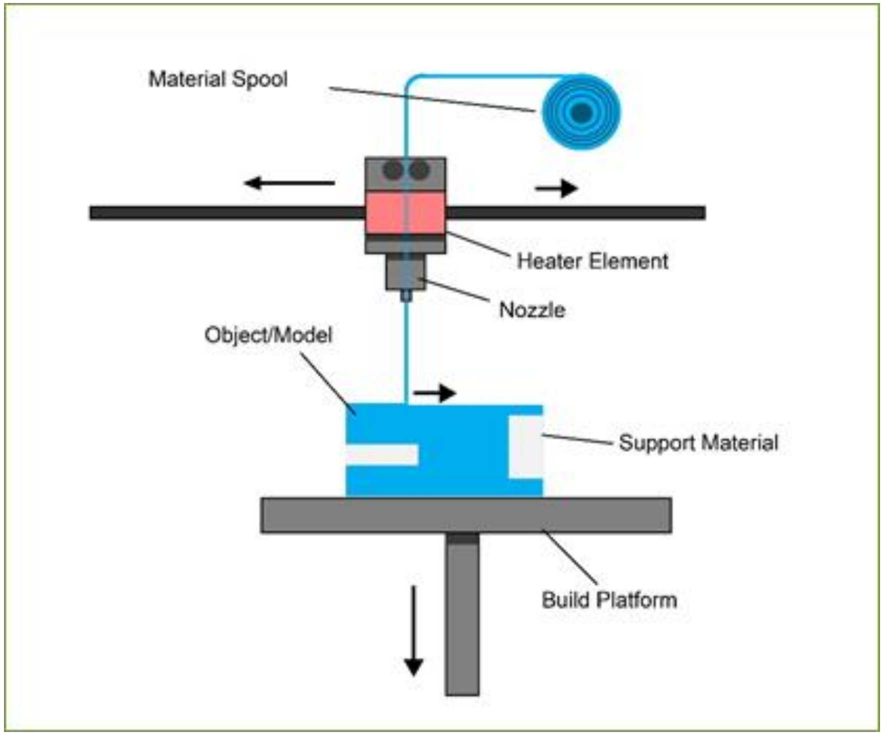
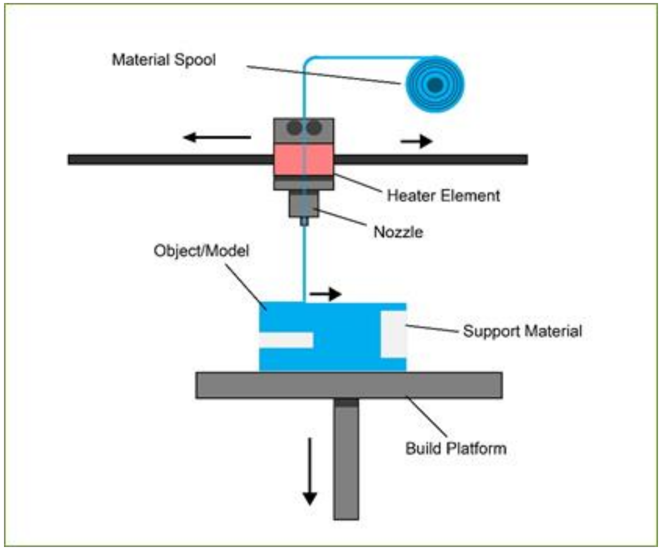


Figure: Material Extrusion process

Picture Source: http://www.lboro.ac.uk/

Material Extrusion



Materials:

The Material Extrusion process uses polymers and plastics.

Polymers: ABS, Nylon, PC, AB

Advantages

- Widespread and inexpensive process.
- ABS plastic can be used, which has good structural properties and is easily accessible.

Disadvantages:

- The nozzle radius limits and reduces the final quality.
- Accuracy and speed are low when compared to other processes and accuracy of the final model is limited to material nozzle thickness.
- Constant pressure of material is required in order to increase quality of finish.

Material Extrusion

https://www.youtube.com/watch?v=WHO6G67GJbM

Binder Jetting

- Powder material is spread over the build platform using a roller.
- The print head deposits the binder adhesive on top of the powder where required.
- The build platform is lowered by the model’s layer thickness.
- Another layer of powder is spread over the previous layer. The object is formed where the powder is bound to the liquid.
- Unbound powder remains in position surrounding the object.
- The process is repeated until the entire object has been made.

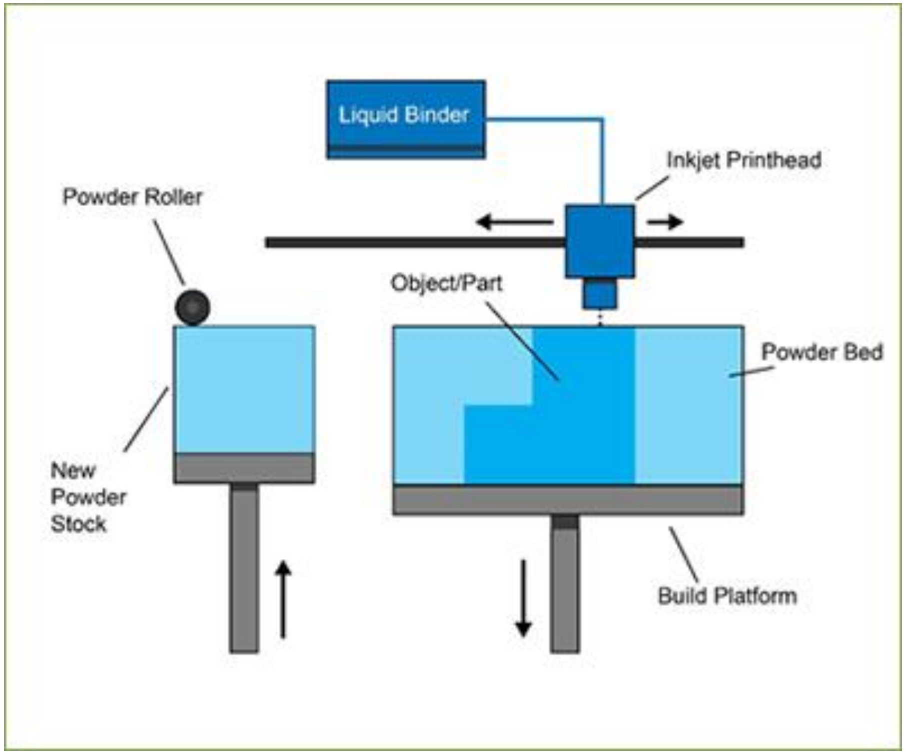
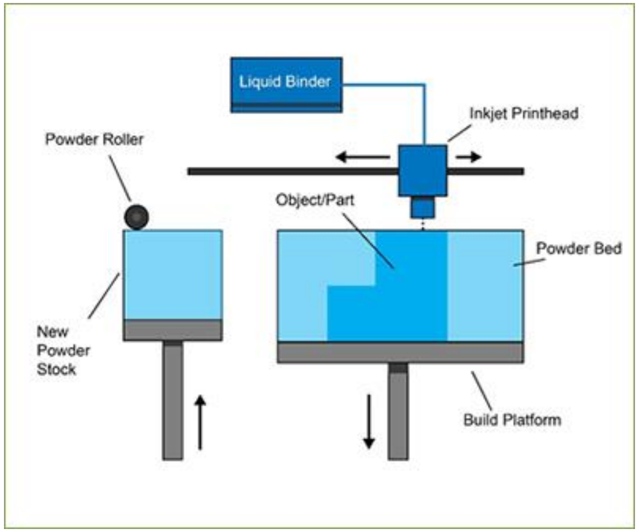


Figure: Binder Jetting process

Picture Source: http://www.lboro.ac.uk/

Binder Jetting



Materials:

Metals: Stainless steel

Polymers: ABS, PA, PC

Ceramics: Glass

Advantages:

- Parts can be made with a range of different colors.
- Uses a range of materials: metal, polymers and ceramics.
- The process is generally faster.
- The two-material method allows for many different binder-powder combinations and various mechanical properties.

Disadvantages:

- Not always suitable for structural parts, due to the use of binder material
- Additional post processing can add significant time to the overall process

Binder Jetting

https://youtu.be/hjIoGPZPNjU?si=krs2mB_Jv2A6P9c9

Process Variants

- Stereolithography (SLA)
  - Microsterolithography (MSL)
  - Two Photon Polhymerization (2PP)
  - Projection Large-area Stereolithography (MPLA-SLA)
- Fused Deposition Modeling (FDM)
  - Precision Extrusion Deposition (PED)
  - 3D Fiber Deposition
  - Precise Extrusion Manufacturing (PEM)
  - Multiphase Jet Solidification (MJS)
- Ink Jet Printing (IJP)/Polyjet
  - Multi-jet Modeling (MJM)
  - Jetted Photopolymer
- Three Dimensional Printing (3DP)
- Laser Engineered Net Shaping (LENS) / Direct Metal Deposition (DMD)
  - Ion Fusion Formation (IFF)
- Selective Laser Sintering (SLS)
  - Micro Laser Sintering (MLS)
  - Selective Laser Melting (SLM)
  - Electron Beam Melting (EBM)
  - Laser Metal Deposition (LMD)
- Selective Mask Sintering (SMS)
- Laminated Object Manufacturing (LOM)
  - Ultrasonic Consolidation (UC)
- Laser Chemical Vapor Deposition (LCVD)
  - Selective Area Laser Deposition (SALD)
  - Selective Area Layer Deposition Vapor Infiltration (SALDVI)
- Direct Metal Laser Sintering (DMLS)
- Controlled Metal Build-up (CMB)
- Drop-on-demand (DOD)
- Focused Ion Beam (FIB)DW
- Laser-induced Forward Transfer (LIFT)
- Matrix-assisted Pulsed-laser Direct Write (MAPLE)
- Pressure-assisted Microsyringe (PAM)
- Low-temperature Deposition Manufacturing
- 3D Bioplotting
- Robocasting
- Direct-write Assembly
- Solvent-cased Extrusion Freeforming
- Rapid Freeze Prototyping (RFP)
- Material Laster-assisted Densification (MMLD)
- Porcelain-fused-to-metal (PFM)
- Freeze-form Extrusion Fabrication (FEF)
- Electrochemical Fabrication (EFAB)
- Laser Direct Writing
- Robotic Dispensing
- Biolaserprinting
- Big Area Additive Manufacturing
- Cold Spray Process
- …

Credit: SURF student

AM Materials

Table 2.1: Additive Manufacturing Process and Material Combinations

	Material extrusion	Material jetting	Binder jetting	Vat photopoly-merization	Sheet lamination	Powder bed fusion	Directed energy deposition
Polymers and polymer blends	x	x	x	x	x	x	
Composites		x	x	x		x	
Metals		x	x		x	x	x
Graded/hybrid metals					x		x
Ceramics			x	x		x	
Investment casting patterns		x	x	x		x	
Sand molds and cores	x		x			x	
Paper					x		

Source: Wohlers, Terry. "Wohlers Report 2012: Additive Manufacturing and 3D Printing State of the Industry." Wohlers Associates, Inc. 2012.

Additive Manufacturing Vendors

TABLE 1 Leading industrial additive manufacturing machine vendors, 1988-2011

Vendors/Production Sites	Processes/Applications	Materials
3D Systemsa (US, AUS, NED, ITA)	Binder jetting, material jetting, vat photopolymerization, powder bed fusion	Plastic, polymer, metal
Beijing Tiertime (CH)	Material extrusion	Polymer
DWS (ITA)	Vat photopolymerization	Polymer
Envisiontec (GER, US)	Vat photopolymerization , material extrusion	Biomaterial, ceramic, polymer
EOS (GER)	Powder bed fusion	Ceramic, metal, polymer
ExOnea (US, GER, JPN)	Binder jetting	Ceramic, polymer, metal
Objetb (ISR, US, GER, Asia)	Material jetting	Biomaterial, polymer
Solidscape (US)	Material jetting	Plastic
Stratasys[a, b] (US, GER, IND)	Material extrusion	Polymer
Z Corp. (US)	Powder bed fusion	Plastic, metal

Sources: Wohlers, *Wohlers Report 2012*, 2012, 135, 136; "Introduction to Additive Manufacturing," Ceramic Industry, December 2012.

[a] Stratysys acquired Solidscape in 2011, and merged with Objet in 2012; 3D Systems acquired Z Corp. in 2012.

[b] Also fabricates parts.

https://www.usitc.gov/journals/Vol_VI_Article4_Additive_Manufacturing_Technology.pdf

AM Shipments

TABLE 2 U.S. Additive manufacturing (AM) shipments, 2011

Category	Relevant industry NAICS codes	Shipments of US-made AM products (billion $)[a]	Total industry shipments (billion $)	AM share of total industry shipments (percent)[b]
Motor vehicles	3361, 3362, 3363	0.048	445.3	0.01
Aerospace	336411, 336412, 336413	0.030	157.7	0.02
Industrial/business machines	333	0.027	365.7	0.01
Medical/dental	3391	0.037	89.5	0.04
Government/military	336414, 336415, 336419, 336992	0.015	32.8	0.05
Architectural	3323	0.074	72.2	0.01
Consumer products/ electronics, academic institutions, and other	All others within NAICS	0.083	895.7	0.01
Total	332 through 339	$.25	$2,058.9	0.01

Source: Thomas, Economics of the U.S. Additive Manufacturing Industry (prepublication draft), June 2013.

[a] These values are calculated assuming that the percent of total additive manufacturing made products for each industry is the same for the U.S. as it is globally. It is also assumes that the U.S. share of AM systems sold is equal to the share of revenue for AM products.

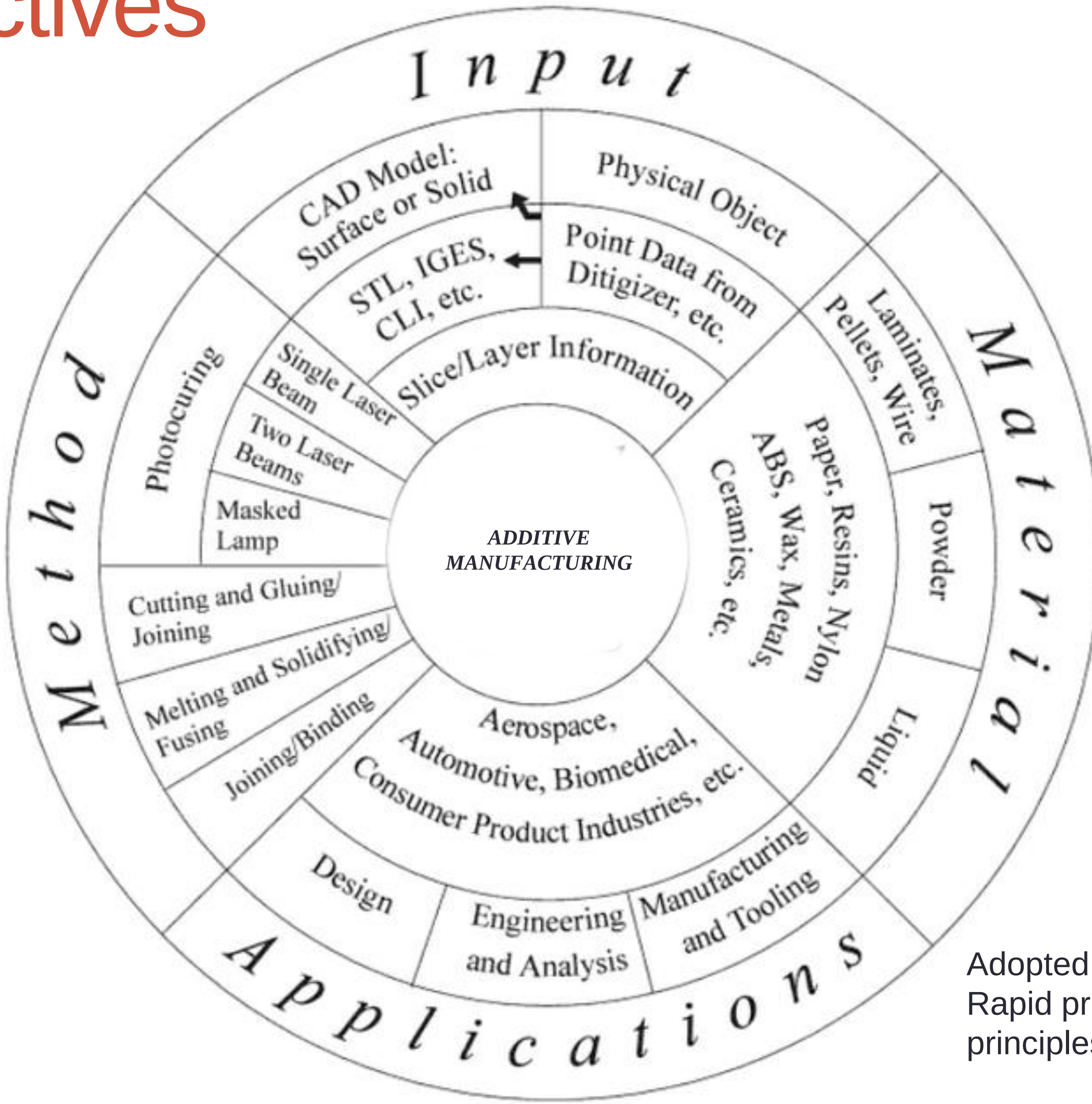
[b] If rounded to "1" right of decimal.

Note: Numbers may not add up to total due to rounding.

*Note: For the purposes of this article, motor vehicles and automotive are used interchangeably.

**Note: The primary additive manufacturing market consists of all products and services directly associated with additive manufacturing processes, worldwide.

Perspectives



Adopted from
Rapid prototyping: principles and applications

Why is Additive Manufacturing important?

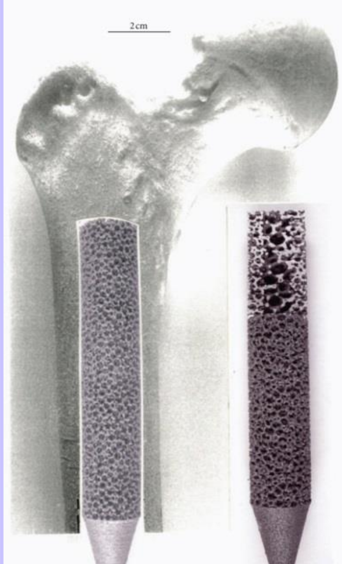
Reduces

- Manufacturing time and cost.
- Material waste.

Geometric complexity—independent of manufacturing cost

Allows

- Complex geometries.
- More customization.
- Faster time-to-market for critical components.
- Changes to traditional supply chain.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Applications

- Aerospace
- Architecture
- Armament
- Art
- Automotive
- Energy
- Electronics
- Fashion
  - Jewelry
  - clothes
- Furniture
- Food
- Maintenance & repair
- Medical
  - Implants and prosthetics
  - Surgical/aid devices
  - Dental
- Spare parts
- Sports
- Textiles
- Tooling/molding
- Toys/Collectibles

Pursuing the Promise

Source: http://energy.gov/sites/prod/files/2013/12/f5/additive_manufacturing.pdf

U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy ADVANCED MANUFACTURING OFFICE

Additive Manufacturing: Pursuing the Promise

Digital manufacturing paves the way for innovation, mass customization, and greater energy efficiency as part of the national all-of-the-above energy strategy.

Thin metal foil is being loaded into an additive manufacturing welding system that uses sound to print parts from dissimilar metals like aluminum, copper, steel, and titanium. *Photo courtesy of Fabrisonic.*

Additive manufacturing techniques create 3-D objects directly from a computer model, depositing material only where required. These new techniques, while still evolving, are projected to exert a profound impact on manufacturing. They can give industry new design flexibility, reduce energy use, and shorten time to market. The process is often called 3-D printing or digital manufacturing because of similarities to standard desktop printing.

Interest in additive techniques has grown swiftly as applications have progressed from rapid prototyping to the production of end-use products. Additive equipment can now use metals, polymers, composites, or other powders to "print" a range of functional components, layer by layer, including complex structures that cannot be manufactured by other means.

The ability to modify a design online and immediately create the item—without wasteful casting or drilling—makes additive manufacturing an economical way to create single items, small batches, and, potentially, mass-produced items. The sector-wide ramifications of this capability have captured the imaginations of investors.

Revolutionary Speed, Efficiency, Optimization

Additive manufacturing has the potential to vastly accelerate innovation, compress supply chains, minimize materials and energy usage, and reduce waste.

- *Lower energy intensity:* These techniques save energy by eliminating production steps, using substantially less material, enabling reuse of by-products, and producing lighter products. Remanufacturing parts through advanced additive manufacturing and surface treatment processes can also return end-of-life products to as-new condition,[1] using only 2–25% of the energy required to make new parts.[2]
- *Less waste:* Building objects up layer by layer, instead of traditional machining processes that cut away material can reduce material needs and costs by up to 90%.[3]
- *Reduced time to market:* Items can be fabricated as soon as the 3-D digital description of the part has been created, eliminating the need for expensive and time-consuming part tooling and prototype fabrication.
- *Innovation:* Additive manufacturing eliminates traditional manufacturing-process design restrictions. It makes it possible to create items previously considered too intricate and greatly accelerates final product design. Multi-functionality can also be embedded in printed materials, including variable stiffness, conductivity, and more. The ability to improve performance and functionality—literally customizing products to meet individual customer needs—will open new markets and could improve profitability.
- *Agility:* Additive techniques enable rapid response to markets and create new production options outside of factories, such as mobile units that can be placed near the source of local materials. Spare parts can be produced on demand, reducing or eliminating the need for stockpiles and complex supply chains.

1 Advanced Manufacturing Office, U.S. DOE, "Materials: Foundation for the Clean Energy Future," January 2012. http://energy.tms.org/docs/pdfs/Materials_Foundation_for_Clean_Energy_Age_Press_Final.pdf

2 John Sutherland et al., "A Comparison of Manufacturing and Remanufacturing Energy Intensities with Application to Diesel Engine Production," *CIRP Annals—Manufacturing Technology*, vol. 57, no. 1 (2008): 5-8.

3 *The Economist*, "The Printed World: Three-dimensional printing from digital designs," 10 February 2011. www.economist.com/node/18114221

Discussion

- 3D opportunity for production

https://www2.deloitte.com/content/dam/insights/us/articles/additive-manufacturing-business-case/DR15_3D_Opportunity_For_Production.pdf

Other interesting links

- https://www.youtube.com/watch?v=l3TgmvV2ElQ&list=RDQMOHp5iQFTlQA&index=16
- https://www.youtube.com/watch?v=ihR9SX7dgRo&list=RDQMOHp5iQFTlQA&index=3
- https://www.youtube.com/watch?v=O2thSsQrZUM
- https://www.youtube.com/watch?v=3LBTkLsjHGQ&list=RDQMOHp5iQFTlQA&index=26