MODULE 111: AM HISTORY

Traditional manufacturing includes a variety of processes, such as molding, forming, cutting, and grinding, that shape raw material to create finished parts. These various traditional processes have led to efficient mass production but have limitations that prevent maximizing part complexity, functionality, and mass customization.

Additive manufacturing (AM) helps move industrial production beyond the limitations of traditional manufacturing. In additive manufacturing, which includes 3D printing, engineers create a part design and then convert it to a three-dimensional (3D) computer model. An AM machine turns the computer model into a finished part by stacking and joining layers of material. End-use AM parts often have improved complexity and functionality compared to traditionally manufactured parts.

AM methods also have a number of other uses in manufacturing operations, such as generating prototypes and tooling. Although AM is currently unable to produce large volumes of parts as quickly and cost-effectively as traditional manufacturing, AM technology is rapidly improving as an increasing number of manufacturers use it to enhance, augment, or even replace traditional operations.

Early additive manufacturing equipment and materials emerged in the 1980s with Hideo Kodama creating a product that used ultraviolet (UV) light to harden polymers to create solid objects. Charles Hull invented a vat photopolymerization method, specifically stereolithography (SLA), which was a rapid prototyping tool that manufacturers used to quickly create prototypes.

Initially, AM allowed manufacturers to optimize part design and streamline traditional manufacturing production processes by creating a range of prototypes without needing to invest in new tooling or change machine setups. Since early prototypes were usually made of plastic, they were unable to match the exact physical properties or mechanical properties required for a finished part. As a result, they served as traditional manufacturing design aids rather than end-use parts.

Other AM methods were developed in the late 1980s. A powder bed fusion (PBF) process developed by the University of Texas at Austin in 1986 allowed for the production of metal AM parts. Material extrusion was developed in 1988 by Scott Crump, co-founder of Stratasys, and fused deposition modeling (FDM), a type of material extrusion, is still the most commonly used AM process today. In addition to expanding available build materials, improving AM technology also increased AM part quality. At this point, manufacturers began to create end-use AM parts that surpassed the functionality of traditional parts through increased part geometric complexity and functional complexity that are impossible to produce with traditional manufacturing.

The 1990s saw further development of more AM methods. Despite its advantages, AM lags behind traditional manufacturing in some important areas, such as production rate, or build rate, and part tolerance. These drawbacks currently limit the prevalence of AM use in overall manufacturing, but constantly improving technology is increasing the scope of AM usage.

The AM build process, which stacks and bonds thin layers of material, removes many of the design limitations imposed by traditional manufacturing. For example, AM part complexity is not restricted by the shape of raw material or a tool's ability to reach certain workpiece areas. As a result, manufacturers can focus on optimizing part design to reduce weight, integrating fully functional features, such as hinges and springs, right into the part, and adding unique AM features, such as curved internal channels or irregularly shaped holes.

AM allows engineers to quickly create and test prototypes by minimizing the need for machine setup or tooling adjustments. Additionally, engineers can quickly augment a part design by simply altering a computer-aided design (CAD) file. As a result, AM makes mass customization an economically viable offering for many manufacturers. AM can also help reduce material waste, production costs, and manufacturing system costs.

Despite its advantages, additive manufacturing has some drawbacks. For example, AM methods often have extended production rates, since the layering process often takes more time than traditional manufacturing processes. The layering process is also less precise than traditional manufacturing, leading to less reliable quality assurance and part tolerances. Finally, some AM parts are weaker where the layers meet than they would be if they were made of a solid material.

AM methods can also slow overall production speed because AM parts often require extensive post-processing. Other disadvantages currently include material costs and part size limitations. However, material costs may decline as AM becomes more widespread, and big area additive manufacturing (BAAM) machines are available for manufacturers who can absorb the increased machine and operating costs of creating larger AM parts.

AM is still in wide usage as a rapid prototyping tool as well as a process for creating end-use parts. Additionally, manufacturers have found a number of other uses for AM technology over the years. An important one of these uses is implementing AM as a secondary process. Secondary AM processes include any operation in which AM functions as an intermediary or supportive step for a traditional manufacturing operation, such as using AM to create a mold for sand casting.

When using AM as a secondary process, manufacturers take advantage of AM's ability to create complex parts and traditional manufacturing's faster production rates. Another common secondary AM process is to create assembly tools, such as jigs and fixtures, and guide tools, such as cutting guides. Other secondary AM processes include manufacturing visual aids, repairing damaged metal parts, and cladding traditionally manufactured parts.

1. AM parts are strongest where their layers meet and are bonded.

✔ ○ True ◉ False

2. AM involves cutting or grinding raw material into a part.

○ True ◉ False

3. Traditional manufacturing has higher production rates than AM.

✔ ◉ True ○ False

4. An advantage of layering material to create a part is that it allows for greatly increased complexity and functionality.

✔ ◉ True ○ False

5. AM is helping make mass customization economically feasible for manufacturers.

✔ ◉ True ○ False

6. AM was originally developed as a tool to create end-use parts.

○ True ◉ False

Most AM operations follow the same basic process to move a part from design to completion.

During the design stage, an engineer creates a 3D part model using a CAD program. AM operations require the use of computers in order to communicate with AM machines and to design and create part programs. Computer networking, which uses cables or a wireless router, streamlines AM operations by allowing one computer to instantly communicate with and control several AM machines.

The machine interface or a specialized computer program translates the CAD data to an AM-compatible file format, usually an STL file. An engineer or machine operator uses a slicing program to generate a G code file from the STL file and transfers the G code file to an AM machine. The operator prepares the AM machine by loading build materials, leveling the build platform, and performing any other required setup. Once the AM machine builds the part, the operator removes the part and performs the necessary post-processing, such as support structure removal and heat treatment.

Most AM processes fit into one of seven process classifications defined by the standards published by ASTM International. Of the seven categories, three processes use a device that deposits the build material.

Material extrusion forces heated build material through a nozzle, depositing thin lines of material on a build platform. These lines collectively form a part layer, and the layers are stacked on top of each other to form the finished part. Material extrusion uses polymers, composites, ceramics, and biomaterials to create parts, with manufacturers currently developing other build materials.

Material jetting involves a printer head, which deposits droplets of liquid or liquid-like material on the build platform in a layer. A UV light in the printer head immediately cures the build material to begin creating the solidified part layers. The layers are formed successively to create the completed part. Material jetting uses polymers and waxes as build material.

Directed energy deposition (DED) is similar to material extrusion, only it creates parts from powdered metal or metal wire. The metal build material is fed in through a nozzle which uses thermal energy from a heat source, such as a laser or electron beam. The heat source melts the material as it is fed or blown out of the end of the nozzle into a melt pool on the build platform. The molten material solidifies to create a part layer.

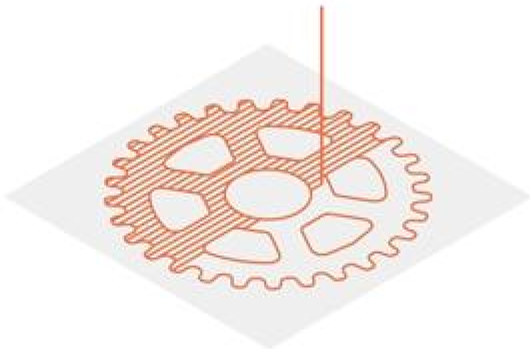
The other four AM processes involve manipulating build material held in a vat or powder bed or on a feedstock roll.

Vat photopolymerization uses UV light to selectively cure specialized forms of liquid-like photopolymers, sometimes referred to as resins. The UV light cures the part in layers, and the build platform rises or lowers, depending on the machine, so that the next layer can be stacked on the first.

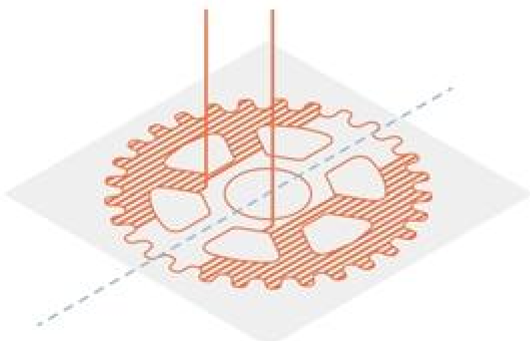
PBF operates similarly to vat photopolymerization, only it uses a heat source, such as a laser or electron beam, to fuse powdered material held in a powder bed. A build platform in the powder bed lowers so that the next layer can be fused on the previous one, and the process is repeated to create the finished part.

Binder jetting selectively places a binder in powdered material to create layers of the part. A printer head deposits binder in powdered material held in a powder bed, and then a heater follows to solidify the binder. As with PBF, a build platform in the bed lowers, so that the next layer can be stacked on the first. Binder jetting can use polymer, metal, ceramic, and composite materials.

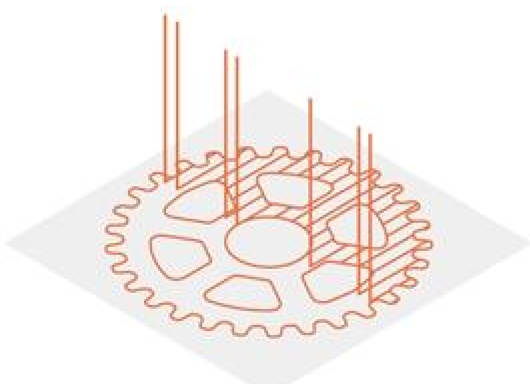
In sheet lamination, a heat source or cutting tool cuts the part layer from a thin sheet of build material. A roller moves over the layer to fuse it to the previous layer using heat, pressure, a combination of the two, or sometimes another fusing method. The build platform lowers, and the feedstock roll unrolls to provide the next layer of material for the heat source or cutting tool to cut into shape. This process repeats until the part is complete.



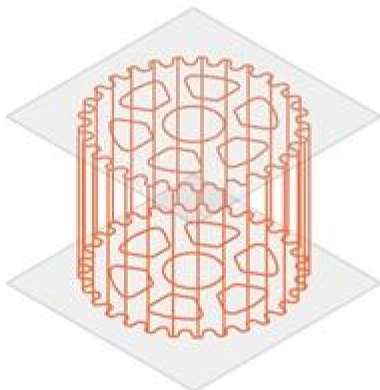
In 1D channel layer construction, a single-point source, such as a nozzle or laser, creates individual lines of material that eventually merge to form a single part layer. Material extrusion and DED always use 1D channel construction, but the vat photopolymerization and PBF processes may also use 1D channel construction.



In 2 x 1D channel layer construction, two single-point sources work simultaneously to create a part layer, either to build one part more quickly or to build multiple parts at the same time. While 2 x 1D construction is usually only possible with more expensive AM machines, it can improve production rates and productivity. Both the vat photopolymerization and PBF processes can use 2 x 1D channel construction.



A 1D channel array uses a series of interconnected single-point sources, such as in a printer head, to deposit multiple material lines in one pass and create a part layer. Currently, only material jetting and binder jetting methods use 1D channel arrays. However, material extrusion and PBF processes may potentially start using 1D channel arrays to improve production rates beyond even 2 x 1D channel methods.



2D channel layer construction uses a source to create an entire part layer at one time. 2D channel construction is the newest and fastest layer construction technique, but it currently has limited applications. The only AM process that uses 2D channel construction is a vat photopolymerization process called continuous liquid interface production (CLIP). In CLIP, a UV projector cures an entire layer of liquid polymer as the part is drawn out of a vat.

An AM process in which a printer head deposits liquid droplets on a build platform.	✔ Material jetting
An AM method in which an adhesive is placed in powdered material to create layers.	✔ Binder jetting
An AM method in which a UV light is used to cure liquid plastic in layers.	✔ Vat photopolymerization
An AM method in which heated material is forced through a nozzle and deposited in layers.	✔ Material extrusion
An AM method in which metal powder or wire is melted by a laser as it is funneled through a nozzle.	Directed energy deposition
An AM method in which a laser sinters granulated material into a solid part layer by layer.	Powder bed fusion

Because AM builds parts layer by layer, rather than removing material from a workpiece or molding material, AM imposes few design restrictions. AM allows engineers to design highly complex parts to ensure that they are optimally functional. The process of developing AM part specifications is known as design for additive manufacturing (DFAM).

AM methods can create shapes and features, such as lattice structures, that are hard to make using traditional manufacturing processes. AM also easily creates undercuts and other features that are challenging for traditional manufacturing. In addition, AM allows for part integration, functional complexity, and geometric complexity, all of which help reduce assembly time and improve functionality. AM parts, through unique features like lattice structures, can also reduce part weight without sacrificing important properties like strength and fatigue resistance.

Each AM method imposes some design limitations and requires specific design considerations. There are varying restrictions for design features, such as wall thickness and hole proximity. Some methods may create parts with thin walls that have the potential to warp. Adding ribs to these walls can prevent warping.

There are a wide range of available AM materials. Although AM materials include ceramic, composites, and biomaterials, such as cells, tissues, and bone, the most common AM materials are polymers and metals.

Polymers, which include plastics, are used in several AM methods, including material jetting, material extrusion, and vat photopolymerization. AM polymers are available in a variety of forms, such as pellets, filaments, liquid photopolymers, and powders. Polymers are useful in creating everything from rough prototypes to polished end-use parts.

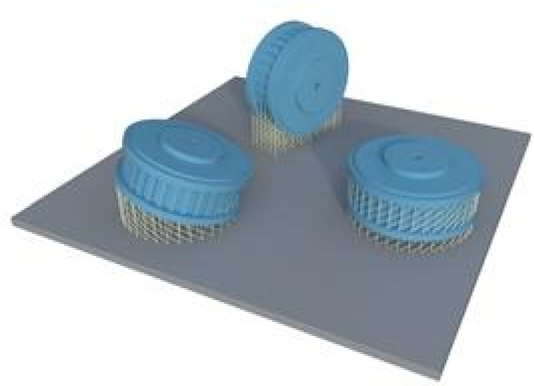
Metals are also used in several AM methods. PBF and binder jetting use metal powder, while DED uses either metal powder or wire. Metal AM methods and processes can use almost any metal, though some better withstand the AM heating and cooling cycles that may lead to thermal distortion. Manufacturers mostly use metal to create end-use parts, particularly for the aerospace and automotive industries.

Composites, such as carbon fiber, are materials reinforced with fibers and provide one of the highest strength-to-weight ratios. Composites can be used in material extrusion and sheet lamination. Ceramics are materials consisting of inorganic compounds that possess increased strength and hardness. Some ceramics used in AM include metal oxides, carbides, glass, and a silica-filled photo polymer known as a ceramic resin. Ceramics can be used in material extrusion, binder jetting, and some types of vat photopolymerization.

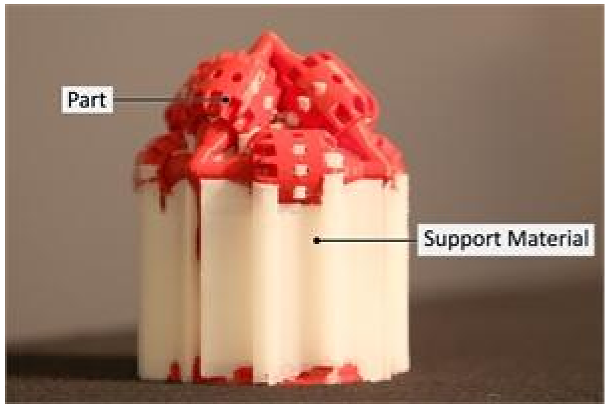
There are a wide range of AM machine types and manufacturers for each AM method. In general, part quality depends on the type of machine. For example, more advanced, and usually more expensive, machines generally produce parts with better accuracy and tolerance. Advanced machines are also capable of creating more complex shapes and facilitating material gradation as well as variations in color, texture, and sometimes microstructure. Since these machines tend to be larger, they also allow manufacturers to build parts in a wider range of sizes.

Currently, an AM machine can only perform one type of AM process. For example, a vat photopolymerization machine cannot perform material extrusion or jetting. Before selecting a machine, manufacturers have to assess which AM method or process best fits their operation and how they would like to use AM. Purchasing a more advanced material jetting machine might make sense for manufacturers hoping to produce high-quality end-use parts, while a small, inexpensive material extrusion machine may serve the needs of a manufacturer who only needs to quickly create visual aids or conceptual models. AM machine manufacturers provide customers with detailed specifications of their machines and may be able to help assess the needs of a part manufacturing operation. All AM machines are automated, so operators communicate with an AM machine using either a computer or the machine interface.

When designing an AM part, engineers must consider how to position the part for the build process and what support the part may need during that process.



Part orientation refers to the position of an AM part as it is built by an AM machine. Part orientation affects the rate of production, the placement and number of necessary support structures, the part's mechanical and physical properties, and the part's surface finish.

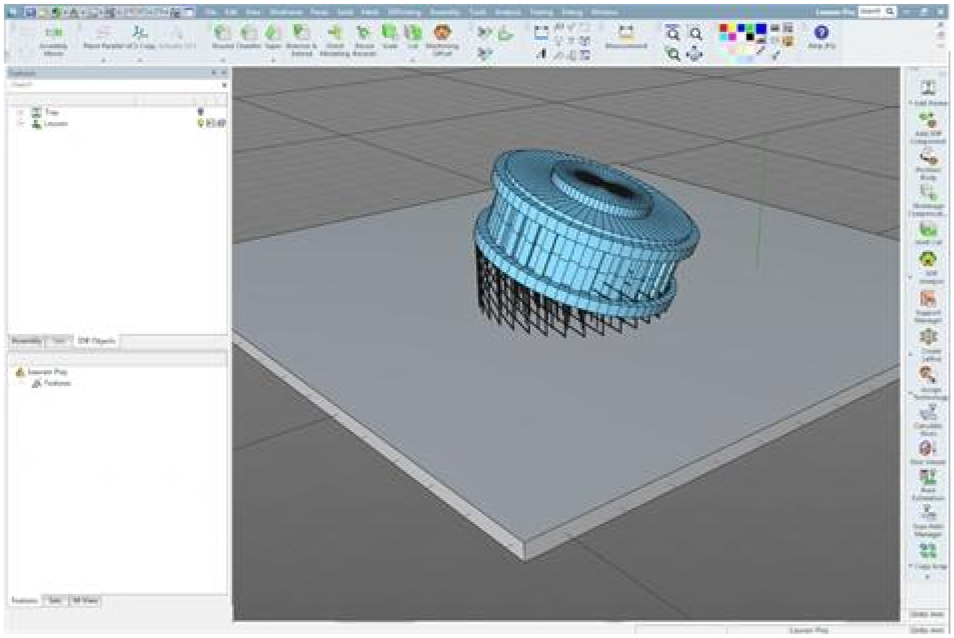


Support structures are removable components that reinforce a part during the AM machine build process. AM machines can make support structures using a separate support material or even the same material as the part but less dense in order to facilitate their removal. Removing a support structure can cause part damage or defects, so support structure design must balance the need for support with the possibility of defects.

AM parts often require some form of post-processing. Post-processing refers to the various procedures, such as cleaning, abrasive finishing, and painting, that are necessary to prepare a part for use. The exact type of post-processing that a part needs depends on its intended use and the AM method used to build it. In general, end-use parts and metal parts require more post-processing than plastic parts or parts that will serve as visual aids or conceptual models.

Some AM parts may require cleaning to remove excess build materials. For example, plastic PBF parts often undergo air blasting, while vat photopolymerization parts usually require an isopropyl alcohol bath. Many AM parts also require the mechanical or chemical removal of support structures or a combination of those methods. Support structure removal can cause surface defects that must be smoothed with abrasive finishing. Manufacturers also use abrasive finishing, including grinding and sanding, to smooth layer lines and improve the appearance and tolerance of AM parts, such as parts produced by FDM. Metal AM parts often undergo heat treatments to improve their mechanical and physical properties. There are a number of other post-processing techniques, such as electroplating and sealing, that can improve part appearance and functionality.

AM engineers use CAD software to create 3D models of a part, often based on a print. Engineers or operators then use a machine to create a finished part that is an exact recreation of the CAD model. However, before it can be processed by the AM machine, the CAD model must be converted to an STL file and then to a G-code file.



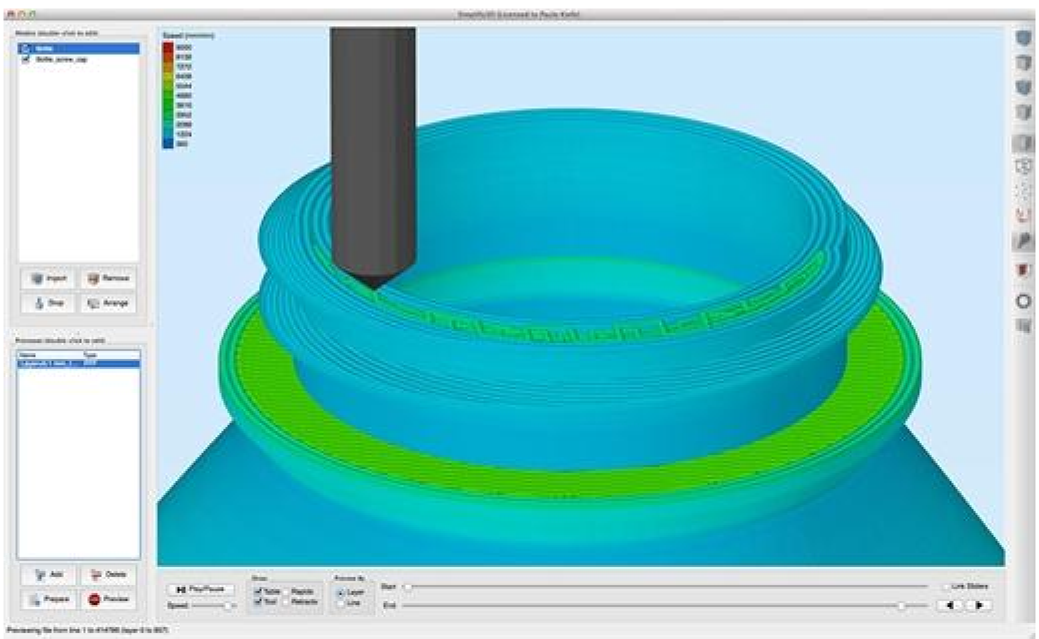
CAD software offers a fast, flexible platform to build 3D models of any size and shape. CAD software also allows engineers to select part resolution and some limited material gradation. AM specialized CAD software provides engineers the ability to examine a design layer by layer, select part orientation, and place support structures during the design phase, rather than when they create the G-code file. In some cases, engineers use more compact types of modeling, such as the less common implicit modeling, which facilitate microstructure and material gradation because they do not rely on boundary representation. Boundary representation defines the limits of a part, typically between the interior and exterior of a part. Eventually engineers may use these more precise modeling techniques in conjunction with or as replacements for CAD modeling.

Although new technology allows engineers to use CAD files directly with AM machines, other common file standards were developed to communicate between CAD software and AM machines. The most common file type is the STL file. Engineers use the label "STL" as an abbreviation for "stereolithography," though they use STL files for all AM methods and processes.

STL files represent the complex, smooth surfaces of a CAD design as a series of separately defined triangles that lack topology. Slicing programs are able to easily slice STL files into the layers that the AM machine reproduces to build the part.

Though easy to use and widely compatible with AM machines, STL files have important drawbacks. For example, STL files can be excessively large, and they do not easily facilitate important AM features, such as changes in a part's color, material, or microstructure. In the future, manufacturers may replace the STL format with more advanced file formats, such as the additive manufacturing file (AMF) format. These improved AM file formats allow for better tolerance and easily allow for varying color, material, and microstructure within a part. These file formats can also use curved triangles, rather than just the flat triangles of STL files, allowing for the creation of more complex shapes. The more advanced file types create more complex parts because they can support more information, often through the use of markup language added to the basic part design.

After creating an STL file or CAD file, an engineer or operator runs it through a slicing program, or slicer, to create a G code file. G code divides the part into layers for an AM machine to recreate. The slicing program also generates the machine toolpaths. Toolpaths are pathways that an AM source, such as a nozzle, will follow to build a part. Though G code is the most common, some machines use proprietary slicers and toolpath files.



Slicing Software. Courtesy of Creative Tools.

Engineers use slicers to create G code directly on the AM machine interface, when possible, or use a separate computer program and then transfer the G code to the AM machine. When using the slicing program, engineers and operators also have the opportunity to select other part and build parameters, such as part orientation and support structure placement. The available parameters vary by process and machine. For example, material extrusion machines might require build speed, shell thickness, and infill information. However, PBF machines may require build speed and laser power, among other build parameters.

Currently, AM is invaluable for rapid prototyping, secondary processes, small-batch production runs, and mass customization. AM use in manufacturing, especially in the medical and dental industry for the rapid production of customized medical implants, is likely to increase in the future and become the dominant production technology.

However, the question facing the AM industry is how much it can grow within the scope of overall manufacturing. The sale of AM parts and services has grown to nearly $12 billion of the $14 trillion manufacturing industry. Industry experts expect AM growth to continue, with AM potentially becoming a $26.6 billion industry by 2027.

Important barriers to AM growth include material costs, slow production rates, poor repeatability, variable part tolerance, slow manufacturer adoption of the technology, and construction size limits. However, AM technologies continue to address these issues. With 51% of manufacturing companies actively using AM methods, AM will become a more mainstream form of production. Ceramic and composite material for AM is gradually improving and becoming less costly, which will result in more variety of end-user parts. Additionally, design software and artificial intelligence (AI) is becoming more integrated with AM technology, and AM machines are becoming more connected thanks to the Industrial Internet of Things (IIoT). Hybrid manufacturing, an AM process that is gaining popularity, allows manufacturers to combine the strengths of traditional and additive manufacturing into one process to make a part. For example, AM may fuse layers together to form the basis for the part, and computer numerical control (CNC) machining completes or finishes the part. The rate at which AM technology improves will determine its future use in overall manufacturing.

1. An additive manufacturing file (AMF) is composed of a series of curved triangles.

- [x] True
- [ ] False

2. CAD is a solid modeling tool.

- [x] True
- [ ] False

3. Computer networking facilitates easy communication between computers and manufacturing machines.

- [x] True
- [ ] False

4. STL files are used to design and create 3D part models for AM.

- [ ] True
- [x] False

5. AM revenue has already reached about half of the overall manufacturing industry market.

- [ ] True
- [x] False

6. STL file formats allow operators to easily program design features such as changes in material, color, and microstructure within a part.

- [ ] True
- [x] False

RESTART

121: AM SAFETY

Importance of AM safety

Additive manufacturing (AM) refers to a variety of methods that create parts by layering material or selectively fusing material in layers. Unlike traditional manufacturing methods, such as casting and turning, AM does not involve cutting or forming material or assembly. Rather than removing material or combining components to make a part, AM equipment creates a complete part, based on a three-dimensional (3D) computer model, in one operation through the addition or depositing of material.

Additive manufacturing includes a range of methods, technologies, materials, and equipment designs. Common AM materials include polymers, metals, and ceramics. AM machines also range in size, from commercial desktop units to advanced equipment capable of producing aerospace components and medical devices.

Despite being a mostly automated process and using machines that are often enclosed, AM poses some safety risks. Operators must be able to identify and respond to hazards such as heat sources, harmful materials, skin irritants, heavy equipment, and dangerous chemicals. Although the various AM methods and processes involve unique equipment designs and different materials, there are some common safety precautions operators can follow to protect themselves and others.

For safety purposes, operators must have an understanding of a facility's equipment and processes. Manufacturers classify most AM methods using seven general categories:

- Vat photopolymerization creates highly detailed plastic or ceramic parts by curing a liquid photopolymer with an ultraviolet (UV) light.
- Material extrusion forces heated material, usually some form of polymer, through nozzles that layer the material to create a part.
- Powder bed fusion (PBF) uses a heat source, usually lasers, to selectively fuse layers of powdered material.
- Material jetting uses a printer head to place droplets of liquid photopolymer on a build platform. The printer head is followed by a UV light that cures the droplets into a part layer.
- Binder jetting selectively deposits droplets of binder in a powdered material to create part layers. The printer head that deposits the binder is usually followed by a heat source that sets the binder.
- Directed energy deposition (DED) funnels powdered metal or a metal wire through a nozzle into a precisely controlled melt pool created by a laser.
- Sheet lamination methods use a blade or heat source to cut thin layers from paper, metal, or other materials, which are fused together by an adhesive or pressure.

Each of these AM methods can pose a variety of safety hazards.

All AM operators use personal protective equipment (PPE). PPE is any clothing or device worn to prevent injury and minimize exposure to hazards, such as skin irritants or falling objects. Most facilities have specific PPE guidelines, usually based on Occupational Safety and Health Administration (OSHA) standards. OSHA requires manufacturers to provide training on how and when to use PPE.

Protective clothing, such as aprons and coveralls, protects against burns, skin irritants, and radiation. In general, AM operators should wear clothing that covers all or most exposed skin. Certain clothing materials are better for providing particular types of protection. While most types of clothing can provide a barrier against debris that would irritate the skin, heat-resistant materials, such as wool, provide particular protection against burns. Similarly, rubber provides protection from a number of chemical hazards.

Safety glasses and goggles protect the eyes and face from flying debris, while face shields protect the eyes and face from sparks and chemical splashes as well as debris. Face shields provide the most coverage, and therefore protection, while safety glasses provide the least coverage. Face shields and safety glasses can also be fitted with filtered glass to protect against radiation.

Gloves protect the hands and arms from hazards such as heat, chemicals, and electricity. As with protective clothing, gloves come in a range of materials to protect against various hazards. For example, insulated rubber gloves protect users from chemical and electrical hazards, while leather gloves provide heat protection.

Respirators prevent operators from inhaling fumes, gases, and particles. Respirators are essential for operations that involve potential contact with especially small particles, such as those in metal powders. In these situations, operators should use respirators that completely seal around the head and provide air from a motor-powered air filtration unit. These respirators must be rated as explosion-proof.

For some AM methods, a good ventilation system may reduce the need for a respirator. A dust mask may be sufficient protection when handling plastic and other non-metallic powders that are composed of larger particles.

Steel-toed boots, toe guards, and shin guards protect the foot and leg area from damage from falling objects. Though many AM methods do not involve heavy materials or parts, some do. The metal powders and metal parts used and produced by PBF and DED methods, for example, can be very heavy. Additionally, AM methods often involve heavy equipment that could shift and fall without warning, such as a printer head that is not properly secured.

An AM method in which parts are built through the selective curing of liquid plastic.	✔ **Vat Photopolymerization**
An AM method in which parts are built by depositing metal into a controlled melt pool.	✔ **Directed Energy Deposition**
Devices that fit over the lower legs to protect against heat, impact, and other hazards.	**Shin Guards**
Insulated hand coverings that protect users from chemical and electrical hazards.	✔ **Rubber Gloves**
Tight-fitting eyewear that protects against splashes and debris.	✔ **Goggles**
A device with a fine filter that prevents operators from inhaling hazardous fumes or particles.	**Respirator**

All AM processes involve moving parts. Operators can protect themselves from lacerations, bruising, and other injuries by understanding common hazards and using the correct safeguards and safety procedures. Many AM machines will prompt operators to confirm that a machine is properly set up and closed at various stages. Operators should double-check the setup before verifying the prompt and moving to the next step.

Building an AM part may involve rapidly moving nozzles, printer heads, support platforms, and sweeping bars or rollers. Most AM machines have protective enclosures or hoods that completely isolate moving parts during operation. For these machines, close and lock enclosures or hoods and leave them closed during the entire build process. Some machines, in particular commercially available desktop material extrusion machines, are not enclosed. When using these machines, keep a safe distance during the build process and never attempt to reach into the machine while it is moving.

When interacting with machine components that can move, such as when cleaning the machine or loading build material, follow all guidelines indicated by the manufacturer. Manufacturers often recommend de-energizing the machine or disengaging the stepper motors before interacting with moving parts. Operators should also remove any loose clothing, jewelry, or employee badges and tie back long hair, which could get caught in the machine. Each machine has unique guidelines about necessary physical clearances or distances that must be maintained around the machine to ensure safe operation and maintenance.

AM equipment is powered by electricity and often includes high-voltage power supplies and complex wiring. If not properly used or maintained, electrical equipment can become overloaded or damaged. Overloaded or damaged circuits can short circuit, overheat, spark, and catch fire. Touching damaged or live wires can lead to severe injuries, including contact burns and electric shock.

To protect against electrical hazards, conduct regular inspections and follow all the machine manufacturer's guidelines. Operators should also inspect power cables for signs of wear, and inspect visible circuitry and wires for signs of damage, such as burns. Immediately stop operations and de-energize machines in order to replace damaged or worn components.

In addition to conducting regular inspections, operators must also follow important electrical safety protocols. Keep electrical equipment away from liquids and humid environments. Additionally, ensure that a machine is properly grounded and plugged into a dedicated circuit that can handle the machine's power requirements. Using adapters, power strips, or flexible wiring, such as extension cords, can increase shock and fire risks because many machines have specific voltage and amperage requirements that must be accommodated. Finally, always turn off and disconnect a machine from the power source when interacting with any component in the machine that could be electrified.

Many AM methods generate heat. For example, nozzles on material extrusion machines can reach temperatures as high as 446°F (230°C). PBF and DED methods require a laser, electron beam, or other high-temperature heat source to melt and fuse the powdered material. Other methods use heated components, such as heated build platforms and build chambers and the heated sweeping bars used in binder jetting and sheet lamination.

AM materials are also potential fire hazards. Some liquid photopolymers used in vat photopolymerization, for example, can ignite easily if exposed to sparks or a heat source. However, the greatest material fire hazards in AM are some of the powdered metals used in PBF, particularly powder made of reactive metal. Reactive metal powders, such as certain alloys of aluminum, are pyrophoric and easily catch fire even when exposed to a small shock from static electricity. Additionally, the filters for filtration systems for AM machines that use metal powders will collect particles of those powders and become extremely flammable. These filters must be replaced with great care. Other metal powders that are less flammable than reactive metals should also be handled with care.

Never touch hot surfaces or parts. Allow all parts and heated machine components, such as a nozzle or printer head, to cool completely before handling them and use heat-resistant gloves when handling hot materials. Wear flame-resistant clothing, such as wool, when working with AM machines. Manufacturers should place smoke detectors near the machine and keep all flammable materials away from the equipment. Keep fire extinguishers rated to suppress chemical and electrical fires near all AM operations. For machines that require inert gas, such as DED machines, examine all seals on enclosures or hoods to ensure they are clean and close properly, which prevents oxygen from entering the machine and starting a fire while the machine is running.

To prevent fires caused by pyrophoric materials, use devices that reduce the possibility of sparks or static electricity, such as non-sparking tools, antistatic mats, and antistatic footwear. AM powders should also be transported and stored as detailed by the powder manufacturer. This usually includes keeping the powder in the manufacturer-provided container and storing it in a dry, flame-resistant storage cabinet that has good ventilation. Pyrophoric materials often require special fire extinguishers, usually Class-D, which should be in the manufacturing area.

Many AM methods use devices that emit potentially hazardous radiation. PBF methods all use some form of laser or electron beam, which emit infrared radiation (IR radiation) and ultraviolet radiation (UV radiation). Similarly, vat photopolymerization and material jetting use UV lights, which emit UV radiation. Excessive exposure to IR or UV radiation can lead to eye and skin irritation and, over time, more serious issues such as permanent eye damage and cancer.

Most AM machines with radiation-emitting devices include enclosures or hoods to shield operators. To allow operators to see into the machine, many of these enclosures and hoods have panels made of filtered glass rated to protect against radiation. Operators can also wear face shields or safety glasses with filtered glass, as well as protective clothing and gloves. Check the machine manufacturer's manual for any other guidelines on protecting against radiation hazards.

Some forms of AM powdered material, particularly powdered metal used in PBF, leave ultrafine particles (UFPs) in the air when moved. UFPs are nanoscale particles, which are around one-billionth of a meter in size. For example, a human hair is about 80,000 to 100,000 nanometers at the root. Inhaling high concentrations of UFPs can cause respiratory problems, eye irritation, and headaches and interfere with the lymph system and nervous system over time. Metal powder is particularly hazardous because once it enters the bloodstream, it does not leave.

Many AM material powders can cause skin and eye irritation, respiratory problems, and more serious issues such as pulmonary fibrosis. The fumes of liquid photopolymers can also contain gases and particles that cause respiratory irritation. Though safe in solid form, some material extrusion materials, such as thermoplastic, emit hazardous fumes when heated. Some of the inert gases used in PBF and DED methods can become dangerous in high enough concentrations, leading to issues such as nausea and even suffocation.

Effective ventilation systems are essential to protect against airborne hazards. Most AM machines have either no ventilation system in the machine or just a simple filtered exhaust system that may need additional support, such as connecting the exhaust system to ductwork. Check the machine manual to determine special requirements for ventilation systems outside the machine enclosure.

Generally, effective external ventilation includes fume extractors or exhaust hoods. Fume extractors are better for ventilating the air in a specific area, such as right around a small AM machine. Exhaust hoods can ventilate a larger area such as the space around industrial production-sized machines. Exhaust systems should replace the air in the AM work area at least four times every hour. Operators determine the exact rate at which to set exhaust systems using a calculation based on the rate of air flow and the room size. Ventilation protects against fumes, UFPs, and, in some processes, accidentally leaking gas. In some operations where gas leaks are possible, such as direct metal laser sintering (DMLS), regularly inspect gas lines to ensure there are no leaks.

When handling, moving, or otherwise interacting with AM metal powders, use gloves and clothing that cover all exposed skin. Some materials, such as various material powders, can enter the bloodstream through small cuts in the skin. Additionally, operators should wear complete respirators that seal around the head and provide filtered air to avoid inhaling powder. Ensure the respirator is rated to work with UFPs and is explosion-proof.

There is a range of post-processing procedures that prepare AM parts for their final usage after they are built. Many post-processing steps are common manufacturing operations, such as painting or grinding. Consult safety guidelines for the various post-processing operations before beginning them.

Removing a part from an AM machine can be as simple as using a scraper to separate a plastic part from the build platform. However, some processes are more complex and require additional safety protocols. Removing PBF parts requires proper PPE and ventilation. Some of the excess metal powder can be brushed away, but some will need to be vacuumed using a wet separator to reduce fire hazards. Removing metal parts from the build plate can involve cutting them off with a band saw or removing them with wire electrical discharge machining (wire EDM). Both processes have a number of important safety protocols.

Support structure removal is often the second post-processing step for any AM part. Operators often mechanically remove support structures with their hands or a simple tool such as a pair of pliers. Though PPE is not always required for these processes, gloves can protect skin from sharp part edges and accidental tool slips. Operators often then use chemical baths to dissolve any remaining support material, particularly sharp edges left behind by manual removal. The chemical bath is hazardous to the skin and eyes, so operators may need aprons, goggles, gloves, and extra tools such as tongs. Parts dipped in a chemical bath must be allowed to dry completely and then rinsed to ensure the chemical has been removed. Additionally, the chemical in the bath is a hazardous waste and must be disposed of according to all local, state, and federal government regulations.

Operators use heat treatment with most metal AM parts to increase their strength and other mechanical properties and physical properties. Heat treatment involves the use of special ovens, which present a number of possible fire hazards. Keep any potentially flammable material away from heat-treating ovens, keep them closed when possible, and always use the appropriate PPE when placing and removing parts.

Most AM parts will need some kind of surface finishing process. Surface finishing processes include sanding, filing, and grinding. Operators can often sand or file with just gloves and a dust mask, but grinding involves rapidly moving components that can produce flying debris and cause injury. Safe grinding requires operators to have a detailed understanding of the process, such as how to hold a part when grinding.

Coating is any process in which operators create a protective outer layer to improve the appearance or properties of the part, such as painting or electroplating. Painting, particularly airbrushing, can create hazardous fumes and particles and poses a risk if the paint gets in the eyes or is ingested. Electroplating is an automated process that uses a chemical solution and electricity to coat parts in metal. Operators must use safeguards and take all necessary steps to protect against the chemical and electrical hazards of the electroplating process.

Material handling is a broad category of procedures that includes the transportation, manipulation, storage, and disposal of AM materials and parts. AM machine and material manufacturers may have specific material-handling recommendations tailored to the process and the properties of the material. For example, material extrusion processes use polymer filaments or pellets, which are fairly light and are not considered fire or chemical hazards.

However, the liquid photopolymers used in vat photopolymerization and material jetting methods have more complex material-handling requirements. For example, liquid photopolymer will cure if exposed to direct light. Operators must also wear appropriate PPE to avoid direct contact with the photopolymer, which can cause skin and eye irritation.

AM metal powders pose similar health and safety risks as liquid photopolymers. Additionally, metal powders and the resulting parts are heavy and can crush feet if dropped. PPE, such as steel-toed boots, is essential when transporting metal powder or metal AM parts, particularly parts still attached to the build plate.

Manufacturers should refer to a material supplier's instructions for cleanup and disposal requirements. Nonhazardous materials will have simple cleanup and disposal. For example, operators can simply throw away the sand used in some binder jetting operations. Liquid photopolymer, metal powder, and other materials have more involved procedures.

Clean any equipment used with liquid photopolymer or other polymers with a solvent, such as denatured alcohol. Solvents have their own hazards, usually requiring at least the use of gloves. Most solvents can irritate bare skin, and some pose respiratory or fire hazards. Spills, especially large ones, often require PPE that covers the entire body, along with a respirator, and careful monitoring of work area oxygen levels. Use disposable rags and sawdust or another absorbent material to clean up liquid photopolymer spills. As with unused photopolymer, dispose of clean-up materials by placing all waste in a metal drum or other sealable container for pickup by a hazardous material disposal agency.

Operators must take caution when cleaning machines that use metal powder, especially reactive powders. These powders must be completely removed from the machine according to manufacturer guidelines to prevent accidental fires. AM metal powder cleanup requires similar PPE and ventilation to liquid photopolymer cleanup but generally does not require any chemicals. Operators should use wet methods, such as damp rags or a wet separator, to pick up waste or spilled powder. Powder must be kept away from ignition sources and disposed of according to hazardous waste protocols.

1. Grinding operations are associated with a number of chemical hazards.

✔ ○ True ◉ False

2. Liquid photopolymer should be kept out of direct light to prevent unwanted curing.

✔ ◉ True ○ False

3. One of the hazards of handling AM metal powders is that they are heavy.

✔ ◉ True ○ False

4. Support structure removal can present mechanical and chemical hazards.

◉ True ○ False

5. Excess liquid photopolymer can simply be thrown away.

○ True ◉ False

6. Spilled AM metal powder should be cleaned up using solvents.

○ True ◉ False

In addition to creating mandatory safety training, OSHA also requires that manufacturers follow the Hazard Communication Standard (HCS). The HCS is a set of standards for labeling hazardous materials and developing detailed material information for operators to review at any time. All AM materials and chemicals, including build materials and cleaning chemicals, have unique properties and safety concerns. Some are combustible, while some cause skin irritation or more serious conditions if improperly handled.

HCS labels must contain the following specific information:

- Product identification, including the hazardous material's name or identification number.
- A signal word, either "warning" or "danger," indicating the level of severity of the hazard, with "danger" being more hazardous.
- Hazard statements, which identify and describe the hazards.
- Pictograms, or easily recognizable symbols, illustrating the hazards.

- Precautionary statements, which recommend how operators can minimize exposure and other relevant hazards.
- The contact information for the responsible party, including the name, address, and phone number of the material manufacturer or other responsible party.

Most chemicals in the workplace must be labeled according to these standards, but there are exceptions. For example, if a chemical is transferred into a smaller container for immediate use, operators are not required to label the smaller container.

To comply with the HCS, manufacturers must keep safety data sheets (SDSs) readily available. An SDS provides more details on a chemical or material's composition, hazards, and handling instructions. This information ranges from technical data to guidelines on how to minimize exposure and clean up spills. The primary difference between an SDS and an HCS label is the increased detail in an SDS. Each chemical has its own SDS that is prepared by the chemical manufacturer, distributor, or importer.

Every SDS must be organized into sixteen categories, twelve of which are mandatory. The first mandatory sections are product and company identification, hazards identification, and composition and information on ingredients. Other mandatory categories include first-aid and firefighting measures, recommended PPE, and storage. Optional sections of the SDS can cover ecological concerns and how to transport and dispose of the chemical. While this information may not be in the SDS, manufacturers are still responsible for ensuring that all regulations and laws related to those sections are followed.

Companies typically place safety data sheets in binders at work stations or use electronic copies that can be reviewed at computer stations. AM machine operators should review the appropriate SDS when working with a new process and periodically after that. When there is a question about a workplace chemical's properties or handling procedures, operators should consult the SDS.

AM machine operators need to conduct routine machine maintenance, as outlined by the machine manual, and arrange for repairs to the machine if it breaks. When equipment is down for service, OSHA requires manufacturers to use lockout/tagout procedures to prevent accidental startup and protect maintenance personnel. Only specific authorized employees with lockout/tagout training are allowed to place and remove locks and tags.

Lockout refers to using various locks, blocks, and other devices to keep a switch, valve, or other energy-isolating mechanism fixed in the "off" position. Most lockout devices include locks that require a key to remove. A tagout device is a warning label, usually placed on the energy-isolating mechanism, that tells users that the equipment is being serviced and should remain off. Although lockout and tagout devices are typically used together, tagout devices can be used alone if a lockout is impossible. Tagout devices have visual warnings and text written in any languages in wide usage by the operators.

OSHA has several requirements for lockout/tagout devices. For example, they must include clear instructions, such as "Do Not Start" or "Do Not Open." They must have a standard color, shape, and print format and must be durable enough to withstand harsh work environments. They must also include the name of the operators authorized to attach and remove them. Once the service is complete, an authorized employee can remove the lockout/tagout device.

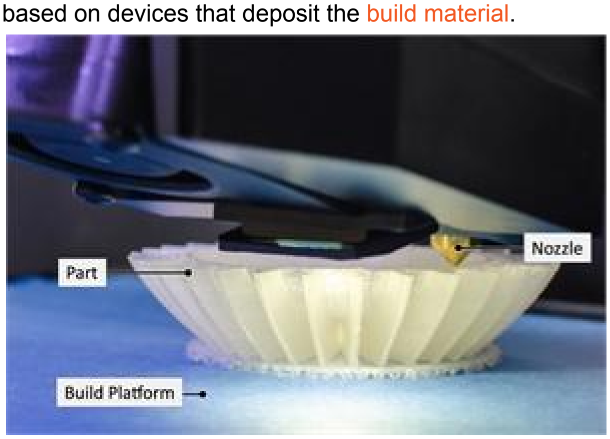
Recommendations on how operators can minimize the hazards of working with a chemical.	Precautionary Statements
Descriptions of the dangers associated with a hazardous chemical.	Hazard Statements
A detailed document that includes information on chemical composition and safety.	Safety Data Sheet
A notice about chemical composition and safety placed directly on a chemical container.	HCS Labels
A component used to hold an energy-isolating mechanism in the "off" position.	Lockout Device
A component used to indicate that a machine is undergoing maintenance or repair.	Tagout Device

131: BASIC AM PROCESS

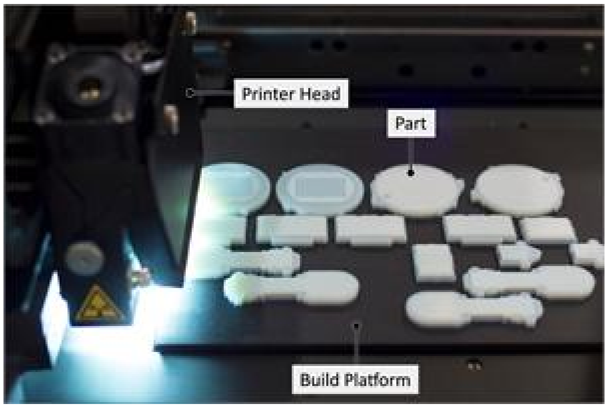
Additive manufacturing (AM) is a set of relatively new production operations that build parts through layering and fusing raw material. In the late 1980s and early 1990s, several different manufacturers developed various AM methods for use as rapid prototyping tools. Since then, however, AM has expanded to other manufacturing applications, both as a secondary process and as a primary process to create end-use parts.

AM includes a variety of methods that utilize a wide range of materials. The number of AM-compatible materials is increasing all the time as manufacturers develop new material types and combinations. There are seven major categories of AM methods: material extrusion, material jetting, directed energy deposition (DED), vat photopolymerization, powder bed fusion (PBF), binder jetting, and sheet lamination. Even though these AM methods vary widely, they often follow the same general process steps.

Most AM methods fit into one of seven categories established by ASTM International. Three of the categories are based on devices that deposit the build material.



Material extrusion involves forcing heated build material through a nozzle and depositing thin lines of material onto a build platform to create a part layer. Material extrusion is the most widely available AM method. It is primarily used to create parts from a variety of polymers. Manufacturers sell polymers in the form of either filaments or pellets when they will be used as AM build materials. However, newer material extrusion machines can make parts using composites, ceramics, and biomaterials. The most common material extrusion process is fused deposition modeling (FDM)



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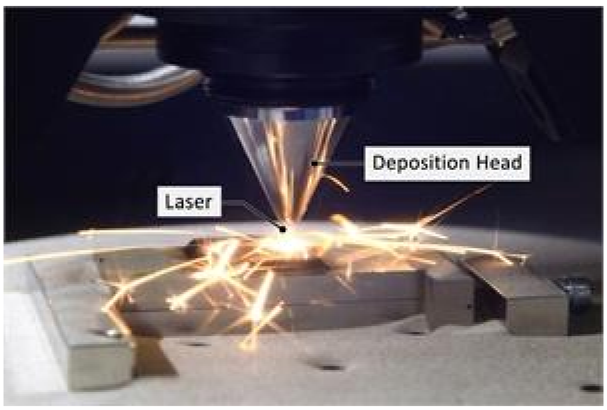
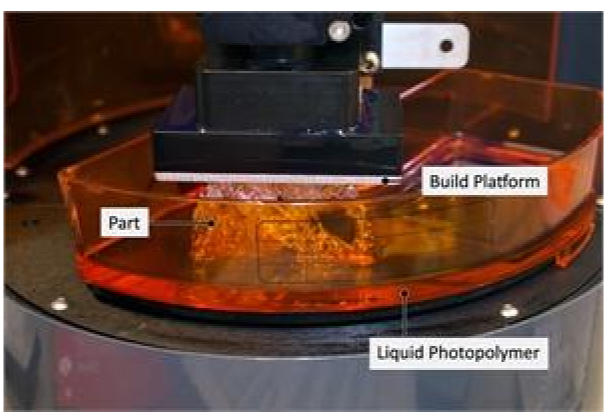
Material jetting methods use a printer head to deposit droplets of liquid or liquid-like material, usually a photopolymer resin. A UV light then cures and solidifies the material in a layer and the build platform is lowered before more material is deposited. Material jetting systems use a variety of polymers and waxes as build materials.

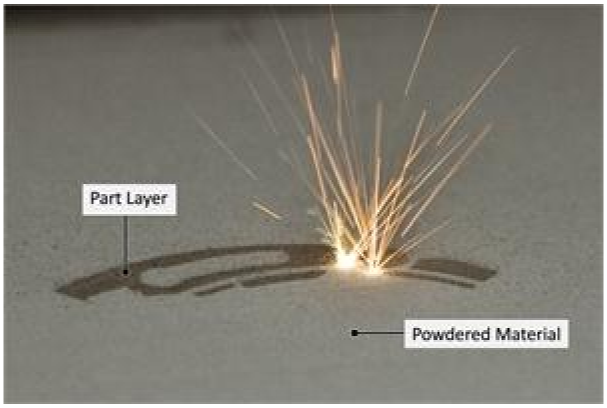


Directed energy deposition (DED) involves using thermal energy from a heat source such as a laser or electron beam, to melt build materials as they are fed or blown through a nozzle into a melt pool on the build platform. The melted material cools and solidifies as it reaches the build platform, eventually creating a part layer. The stacking of these layers creates the finished part. DED uses a variety of metal build materials, which can be either in the form of metal wire or powder. DED includes proprietary methods such as electron beam additive manufacturing (EBAM) and laser-engineered net shaping (LENS).

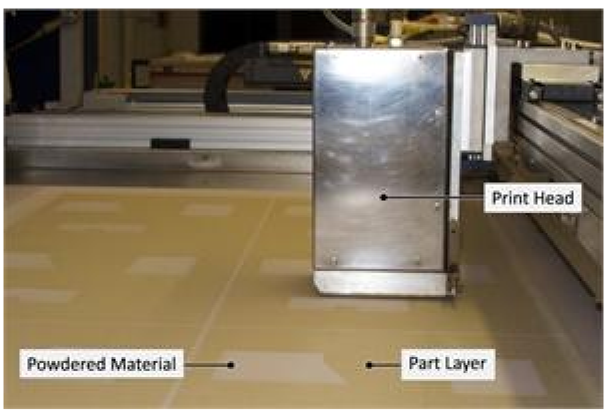
The other four AM categories include methods that manipulate build material held in a vat or powder bed or on a feedstock roll.



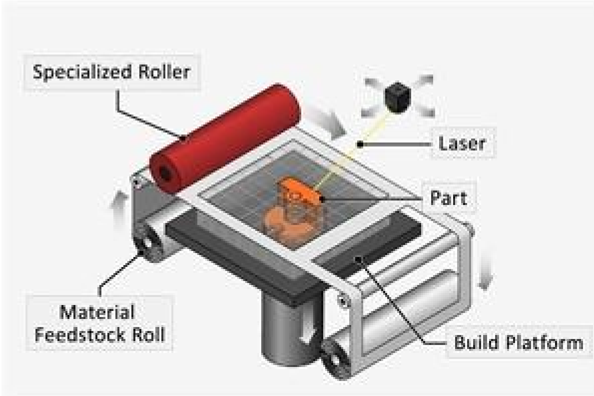
Vat photopolymerization uses a UV light to selectively cure photopolymer, sometimes referred to as resin, in layers to form the part. The photopolymer is held in a vat, and a build platform either lowers into the vat or rises out of the vat depending on the location of the UV light. Vat photopolymerization methods include SLA and DLP. As with material extrusion, vat photopolymerization is primarily used to create parts out of various polymers, but it can also be used to make parts from ceramic.



Powder bed fusion (PBF) methods use a heat source, often a laser or electron beam, to fuse or melt powdered material into solid layers. The material is held in a powder bed, and a build platform lowers into the powder bed as each layer is created. Powder bed fusion processes include selective laser sintering (SLS), which fuses parts out of powdered polymer, and direct metal laser sintering (DMLS), which fuses parts out of powdered metal. PBF also includes selective laser melting (SLM) and electron beam melting (EBM), both of which melt powdered metal at higher temperatures to create solid parts.



Binder jetting methods deposit a binder into powdered material in layers to hold a part together. As with material jetting, the binder is deposited using a printer head. However, instead of a UV light, a heater follows the printer head to solidify the binder. As with PBF, the build material is held in a powder bed with a build platform that lowers after each layer is created. Binder jetting can use polymer, metal, ceramic, composites, or sand.

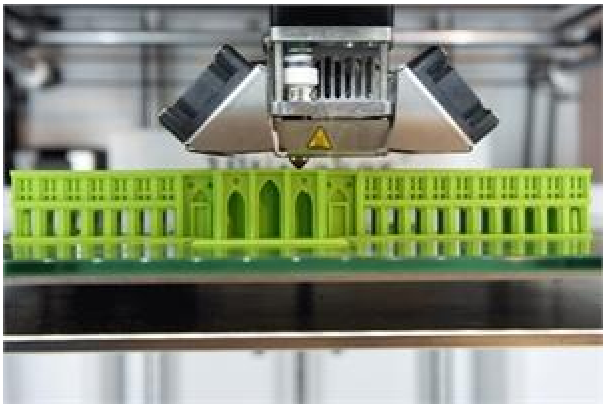


The sheet lamination method uses a heat source or a cutting tool to cut the part layer from a thin sheet of material, usually paper, ceramic, or metal. After a layer has been cut, a roller moves over the newly created layer to fuse it to the previous part layer using heat, pressure, or both. The build platform then lowers, and the feedstock roll, which holds the build material, unrolls to provide another part layer that will be cut into the required shape. Sheet lamination processes used mainly for building conceptual models include laminated object manufacturing (LOM) and selective deposition lamination (SDL). Other advanced sheet lamination methods, such as composite-based additive manufacturing and ultrasonic consolidation, can build functional, end-use parts.

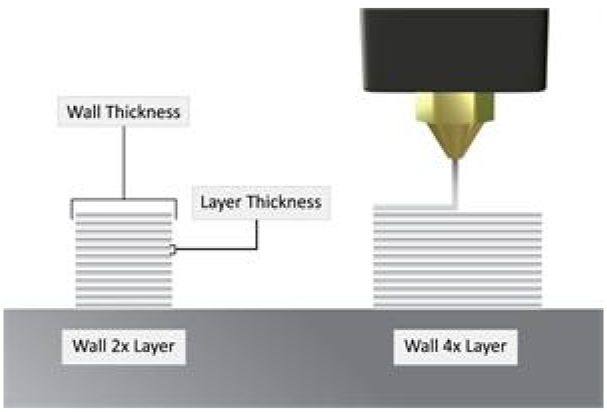
Most AM parts are built using polymer or metal materials. Both material types are divided into a wide range of sub-categories that exhibit a wide range of physical properties and mechanical properties. Manufacturers select the correct material based on the requirements of the application. For example, some polymers have varying degrees of rigidity that are suited to building structural components, such as brackets. Other polymers are ductile and behave more like rubber, which can be useful in creating flexible joints. Metals for AM come in powder, wire, or sheet form. Similar to polymers, there is a huge range of metals, in pure or alloy form, that exhibit a range of properties.

AM build materials also include composite, sand, ceramic, glass, and even biomaterials, such as living cells and tissue. Manufacturers are increasingly using AM to create composite parts, which have excellent strength-to-weight ratios. Manufacturers often create composite parts with material extrusion machines that have a nozzle that dispenses polymers and another nozzle that dispenses carbon fiber to reinforce the polymer. Manufacturers also use binder jetting to create molds from sand, or to create consumer products from ceramic, glass, or metal materials.

In DFAM, engineers often first create a rough sketch of a part's design concept as a print drawing. Once the concept has been edited, refined, and reviewed, engineers then turn the print into a three-dimensional (3D) part model using computer-aided design (CAD) software. Once the finalized CAD model is ready, it is converted to a format that an AM machine can read and the actual AM operation can begin. Throughout the design process, engineers must keep in mind the principles of DFAM, the desired usage of the part, potential build materials, and potential AM methods and processes.



A key DFAM advantage is that AM machines impose far fewer design limitations than traditional manufacturing machines. Since they do not require rigid tooling and workholding devices to machine raw materials of a set shape, AM machines can create parts with much greater geometric and functional complexity. Geometric complexity allows engineers to design parts with a greater variety of shapes than traditional manufacturing. For example, lattice structures are hard to create using traditional manufacturing but easy to create with AM. Lattice structures are honeycomb-like structures in a part's interior that reduce weight while maintaining strength. Functional complexity allows engineers to design moving features, such as joints or springs, right into the part build, eliminating the need for assembly.



However, each AM method also has important limitations, such as minimum wall thickness, layer thickness, hole diameter, and feature size. The exact design limitations will vary based on the specific AM method, part shape, build material, and AM machine. For example, material extrusion parts generally must have walls that are four times thicker than their layers, which can be as thin as 0.0001 in. (0.0025 mm). Binder jetting parts, on the other hand, usually have a general minimum wall thickness of 0.03 in. (0.76 mm). Both methods can create parts with thinner walls, but they will be extremely fragile.

A key DFAM consideration is the desired usage of the AM part. AM parts are used in a variety of ways, including:

- As prototypes, or sample part models, such as conceptual models or functional prototypes.
- In secondary process applications, where an AM part supports a traditional manufacturing operation, such as an AM-created mold being used in injection molding.
- As tooling, such as jigs, fixtures, and cutting tools.
- In end-use applications, where consumers can directly use a part, such as AM-created footwear, or a manufacturer can use the part in a larger assembly, such as an AM-created turbine blade.
- As visual aids for presentations or educational lectures.

An AM part's use will affect the required precision of its design. For example, a conceptual model or visual aid will not need to meet strict and precise tolerances, while an end-use part, particularly for a high-stress aerospace application, will need to meet extremely precise specifications and tolerances. The part's use will also affect whether it needs specific features. For instance, internal channels are useful in tooling, end-use parts, and secondary applications but unnecessary for visual aids or conceptual models. Though engineers may already know the AM method they will be using to build the part, the part's design and use may also help determine the proper AM method and build material.

During part design, an engineer determines the exact material to use to build a part. The type of build material depends on the mechanical properties and physical properties that a part's application requires. End-use, tooling, and secondary applications are likely to require parts made from build materials with more specific properties than a prototype or visual-aid application. For example, engineers designing an end-use turbine blade would likely select a carefully crafted metal alloy, such as a titanium alloy, as the build material. The right metal alloy will give the turbine blade good mechanical and physical properties, such as strength and thermal resistance, respectively. In contrast, an engineer can choose the most cost-effective build material, such as an inexpensive plastic, to create a conceptual model of a tool or part, since manufacturers will only use the model as a step in the process to get an end-use part. In some cases, engineers may test a variety of materials for a single part to see which material works best for that application. The build material may determine the appropriate AM method, or the AM method may help narrow down possible build materials.

Most manufacturers only use one particular AM method. As a result, engineers working for those manufacturers will design parts for just one AM method. However, dedicated AM facilities often use a range of methods and processes and engineers working in these facilities may design parts for all of the AM methods. Similarly, there are also service bureaus for each AM method which take designs from engineers and turn them into parts. These service bureaus enable all manufacturers to take advantage of the entire range of AM technologies even if they do not have them on their premises. In some cases, the AM method will drive DFAM, while the design process may determine the appropriate AM method in others.

Selecting the appropriate AM method requires a thorough understanding of the advantages and disadvantages of each method and knowledge of the part's specifications. For example, material jetting easily creates parts with material gradation, and it is more efficient than some other AM methods. However, though newer build materials are more durable, material jetting parts made of some materials can degrade with exposure to heat, which would make them unsuitable for high-heat applications. From a design standpoint, some methods, such as material extrusion, struggle to create parts with the same tolerance and surface finish quality as parts produced by other AM methods, such as vat photopolymerization. For metal parts, binder jetting is more efficient and cost-effective than powder bed fusion processes, but binder jetting build materials are often weaker and have less fatigue resistance than end-use parts may require. Because of that, binder jetting is generally a better AM method to use when creating prototypes or as a secondary process.

1. An AM limitation is that wall thickness on an AM part should be at least four times the layer thickness in material extrusion.

✔ (●) True ( ) False

2. Engineers should use carefully crafted alloys to create visual aids.

✔ ( ) True (●) False

3. Visual aids model the mechanical and physical properties of a part.

✔ ( ) True (●) False

4. Material jetting can be used to create parts with material gradation.

✔ (●) True ( ) False

5. An AM advantage is that it allows engineers to design parts with great geometric and functional complexity.

✔ (●) True ( ) False

6. AM processes limit part complexity because they use rigid tooling.

✔ ( ) True (●) False

Despite the variety of AM methods, the procedures for a basic AM operation can be broken down into eight general steps, many with important sub-steps. Though the exact order may vary depending on a variety of factors, including the specific AM machine and AM software, the general AM steps are to:

- Create a 3D part model using CAD software.
- Convert the CAD design to an STL file or similar file.
- Transfer the STL file to a slicing program to create a build file.
- Set up the AM machine.
- Run the AM machine to build the part.
- Remove the part from the AM machine.
- Clean the machine.
- Perform any necessary post-processing on the part.

The different AM methods and an AM part's application will change the specifics of how an engineer or operator should perform each step in the operation. For example, to set up a vat photopolymerization machine, an operator will have to pour a photoreactive substance into a vat. However, to set up a binder jetting machine, the operator needs to load binder that will be fed to the printer head and load powdered build material in the printer head or into a separate powder bed for a scraper bar to move into the primary powder bed as needed. Additionally, an end-use AM part will almost always require more post-processing than an AM prototype. Each basic step has similar variations that an engineer or operator will need to assess and implement based on the AM operation.

To build a part, engineers must first create a 3D model that is an exact representation of the AM part using CAD. A basic CAD program allows engineers to build and manipulate highly detailed part models and to define part features and specifications down to a few hundredths of an inch (several tenths of a millimeter) directly on a computer. While most CAD models are based on a part print, engineers may also create a 3D model by scanning and reverse engineering a traditionally manufactured part.

Newer CAD programs have features that engineers can use to design even more complex parts. For example, an engineer can use computer-aided engineering (CAE) features to digitally test a part's response to real-world conditions, such as how it may react to certain amounts of load. CAE also helps engineers with topology optimization and material gradation. Integrating CAD with additional design tools, such as those capable of modeling a build materials or part's microstructure, can also help to improve part design.

Once the design has been finalized and the part is ready, engineers or operators will set part resolution, or the level of part detail and smoothness, while working within CAD. Some CAD programs also allow engineers or operators to determine where to place support structures to best reinforce a part during its build and many do this automatically. Once these selections are made, the part is ready for the next step in the AM build operation.

CAD models contain more data than AM machines can process. As a result, engineers need to convert CAD models into simpler AM-compatible file formats, usually an STL file. STL files represent CAD models as a series of interconnected triangles. Operators refer to these triangles as facets.

While the exact conversion procedure varies, engineers or operators can usually convert CAD models into STL files using the proper action in the CAD software menu. Manufacturers can also download or purchase conversion tool software that is dedicated to converting CAD to STL and then load the CAD model into the software. The software will indicate if there are any flaws, such as gaps in the model or if some facets are oriented incorrectly, that an engineer or operator will need to correct prior to building a part. In some cases, engineers or operators will select how many triangles they would like the part to be divided into during the conversion process. The number of triangles will affect part resolution. For example, parts consisting of more triangles typically have higher resolutions. Higher resolution improves a finished part's surface finish and accuracy. However, if layer thickness is decreased to build a part at a higher resolution, build time increases.

STL files are broadly compatible with AM machines and software and eliminate some of the extra data in the CAD model. For example, STL files do not contain specific measurement units for the model. However, STL files have important limitations. For example, STL files do not easily facilitate material gradation or varying material textures and color. Other increasingly popular AM file formats, such as the Additive Manufacturing File (AMF) format, are available, and these facilitate variation in a part's color, texture, material, and even microstructure.

Converting the CAD model to an STL file is an intermediary step that engineers or operators usually take before creating a build file based off the STL file. Build files contain all the information, including machine toolpaths, print speed, print temperature, layer thickness, infill, and other build parameters, that an AM machine needs to build a part. In many cases, engineers or operators select parameters, such as part orientation and support structure placement, while creating build files. Engineers and operators also usually decide the desired measurement units and part size while creating the build file. The various build file programs engineers or operators use in AM are slicing programs, or slicers, that divide the STL model into the part layers, which an AM machine then physically creates. Slicers automatically generate part layers and toolpaths, but engineers and operators can also manually enter the various build parameters in the program.

For many smaller AM machines, particularly desktop models of material extrusion machines, the slicer is a separate computer program with a unique output file. Engineers or operators then transfer the output file to the AM machine to begin the build process. However, for more advanced machines, such as an industrial powder bed fusion machine, the slicer is part of the machine interface. In these instances, an operator uploads the STL file to the machine, and the machine then generates the build file from the STL file. In some cases, advanced machines can create the build file directly from a CAD model.

The build process can begin once the engineer or operator finalizes the build file, sends it to the AM machine, and initiates the build process. Engineers or operators transfer build files to the AM machine using a network between the computer and AM machine or with some type of external memory storage device, such as a universal serial bus drive (USB drive) or a secure digital card (SD card).

A solid design tool that engineers use to create a 3D model of an AM part.	CAD
Computer software that tests how a part design will respond to real-world conditions.	CAE
A computer file that represents a 3D model as a mesh of interconnected triangles.	STL
A computer file that provides AM machines with build information, such as machine toolpaths.	Build file
The computer program that divides an STL model into part layers for an AM machine to build.	Slicer

Once operators have a build file, they need to correctly set up an AM machine for the particular part build. Operators may also have to set some build parameters while preparing AM machines that are not sophisticated enough to recognize complex instructions in the build file. For example, to prepare a desktop FDM machine, operators will often use machine buttons or dials to set extrusion temperature and build platform temperature rather than entering these parameters in the build file.

Most AM processes require that the operator level the build platform to ensure the AM machine builds the part correctly. A few, such as binder jetting and powder bed fusion, do not require a level bed but do deposit a layer or two of support material to create a level surface on which to build the part. Some AM methods, such as DED, use removable build platforms called build plates, which help make removing the part after the build process easier.

For most AM machine setups, operators will load build materials and support materials, but the exact setup procedures depend on the specific AM method. For example, an operator may have to load several different build materials into a material jetting system machine so it can create parts with material gradation. The operator will also have to ensure that the loaded materials correspond with the varying materials marked out by the build file.

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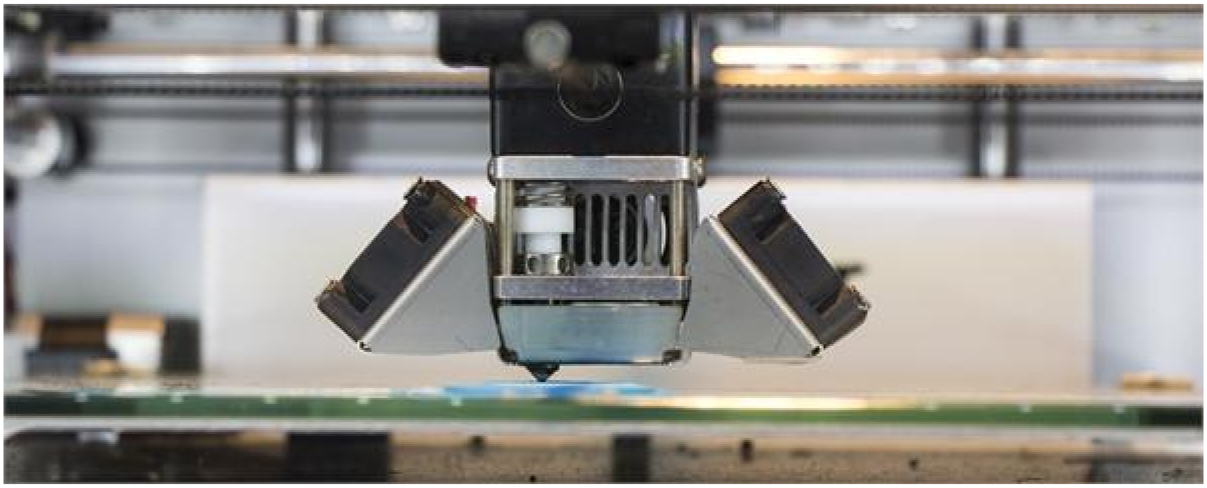
Starting the building step of an AM operation is usually as simple as selecting the build function, or print function, on the AM machine or a networked computer. However, the exact process will vary for every machine. In some cases, transferring the build file from the slicer program to the machine will begin the build process. In other cases, an operator will need to select the build function on the AM machine interface after creating and loading the build file.



Running an AM Machine

Once started, most AM build processes are almost entirely self-sufficient. Most AM machines will calculate the necessary amount of build material for a part in advance so an operator can load the correct amount of material prior to running the machine. However, some may require an operator be on hand to refill build material, especially for long builds and when material is delivered by cartridge, such as in certain material jetting processes. In general, though, AM machines allow for lights-out manufacturing since they can run automatically and without any supervision.

As with the previous steps in the AM operation, part removal varies depending on the AM method and machine.

For example, material extrusion, material jetting, and vat photopolymerization machine operators must carefully separate the part from its build platform. Operators often use mechanical means, such as a scraper, to remove parts from the build platforms of these machines.

Binder jetting and the PBF machine operators must sometimes remove excess powder from around the part before separating it from the build platform. Operators remove the powder either inside or outside of the machine and often use a combination of a brush and vacuum to carefully remove the excess powder. Additionally, since the small powder particles are hazardous and potentially flammable, operators must always wear proper personal protective equipment (PPE), such as gloves and respirators. Some PBF machines have removable build boxes to facilitate powder removal. Operators can take the build box out of the machine and reach the powder with a vacuum more easily. Once operators remove the powder, they separate polymer parts made with binder jetting or PBF methods from the build platform. Operators may need to remove metal parts from the build platform with chisels, saws, or wire electrical discharge machining (wire EDM).

AM machines require cleaning after each operation. For example, AM operators need to clean the build platform or plate for all machines. For material jetting and material extrusion machines, this involves scraping off residual build materials and wiping the surface down with a solvent. Because vat photopolymerization build platforms are submerged in resin, they will sometimes need more extensive treatment. Operators may need to clean the build platform using a chemical bath and then rinse it thoroughly with water. To clean binder jetting or PBF build platforms used to make polymer parts, scraping and cleaning are usually sufficient. However, PBF or DED build plates that were used to make metal parts require operators to resurface them using grinding or milling.

Operators also need to purge, or clean, the nozzles used in material jetting, material extrusion, and binder jetting machines. After the nozzles have cooled, operators can remove any residual build material or binder by scraping the nozzles out with a rigid wire or soaking them in a solvent. Vat photopolymerization machine operators should clean any photopolymer that has spilled outside the vat. Similarly, operators must ensure that they have removed all excess powder from the powder bed of a PBF machine. Operators should also check the interior of the PBF machine, particularly its moving parts, such as the roller, to ensure that trapped powder will not cause the machine to malfunction.

Ultimately, every AM machine has a specific cleaning procedure outlined in its operation guide. Operators should always consult this information to familiarize themselves with the appropriate cleaning processes.

Almost every AM part will need to undergo various post-processing procedures that prepare them for final use. Several factors, including the AM method and build material used to create a part as well as its application, determine the necessary post-processing procedures. Some parts, such as those created using vat photopolymerization, may need a simple rinsing before beginning any post-processing operation.

Post-processing typically begins with the removal of any support structures or support materials. Operators can manually remove some support structures. Others, such as soluble support structures, may require an operator to use a chemical bath or solvent. Sometimes, operators start by manually removing most support material and then dissolving the small remaining pieces of support material with chemicals.

While an AM part that will be used as a rough visual aid may only require support structure removal, most other AM parts require additional post-processing. In particular, since support structure removal may leave defects and layer lines are often clearly visible, abrasive finishing, such as filing, grinding, or polishing, can help improve the quality of an AM part's surface finish. End-use parts may also require coating or painting to improve their physical and mechanical properties or their appearance. Finally, heat treatment is often necessary to improve the properties of metal AM parts, particularly those made for end-use applications.

While all AM methods have their own unique procedures, their overall operations have important similarities.

For DMLS, a PBF process, the operation begins with an AM operator setting up the machine and loading the powdered metal build material. Prior to running the DMLS machine, the operator should close the machine safeguards and then fill the chamber with an inert gas. Afterwards, the operator can typically initiate the build process.

During the build process, a laser traces over a layer of metal powder held on a build plate. The laser selectively sinters and solidifies the metal powders to form a part layer. A roller or scraper bar will then move across the build plate adding a new powder layer over the first, so the laser can begin to sinter the next part layer. This process repeats until the entire part has been built from the bottom layer up.

Once the part is complete, the AM operator must first remove the build plate and excess powder from the DMLS machine. Finally, the operator will separate the part from the build plate and perform any necessary post-processing, such as heat treatment or grinding, on the part.

1. STL or build files are transferred to an AM machine using a CAD connection.

- ○ True
- ● False

2. Removing parts from a powder bed fusion machine includes vacuuming and brushing away excess powder.

- ● True
- ○ False

3. An operator must level an AM machine's build platform or plate before running the machine.

- ● True
- ○ False

4. Post-processing for end-use polymer parts includes heat treatment.

- ✔ ○ True
- ● False

5. Operators resurface material extrusion build platforms after each operation.

- ✔ ○ True
- ● False

6. Lights-out manufacturing refers to building light sensitive parts in complete darkness.

- ✔ ○ True
- ● False

141: AM METHODS AND MATERIALS

Additive manufacturing (AM) is a dynamic field that encompasses many methods, processes, materials, and applications. AM differs significantly from subtractive manufacturing processes, such as grinding and machining, that remove material from a workpiece to create a final product. Instead, AM methods join materials together, usually layer-by-layer, to create a final part based on a computer-generated three-dimensional (3D) model.

AM methods represent a variety of technologies that are constantly evolving as manufacturers continue to make new developments. While manufacturers can categorize AM technologies in a variety of ways, most group these technologies according to the method they use to create parts. For example, some systems build parts by extruding layer upon layer of material, while others use thermal energy to selectively fuse material. Currently, manufacturers recognize seven distinct additive manufacturing methods.

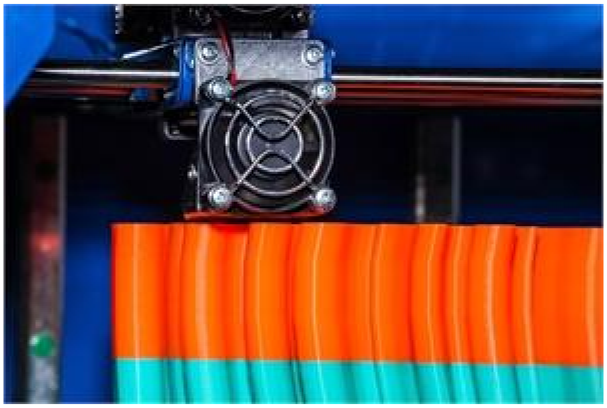
Material extrusion, also known as fused deposition modeling (FDM) or fused filament fabrication (FFF), is one of the most common and widely available AM methods.

Material extrusion systems use an extrusion head with a nozzle to deposit build material onto a build platform. During material extrusion, a filament is fed through the extrusion head by a drive roll and past a heating element. The material liquefies and is then deposited by the nozzle onto the build platform. The extrusion head moves horizontally to selectively dispense a material layer in the shape of the desired part onto the build platform. The build platform, which usually moves vertically, lowers so the nozzle can dispense a new material layer on top of the first layer. Each layer solidifies and joins with any additional layers. This process repeats until the final product is complete.

When adding layers, material extrusion systems sometimes dispense support material along with the build material. Support materials occupy negative spaces and provide stability to disconnected part features, such as overhangs or holes, during the building process. Once the part is complete and prior to its use, AM machine operators must remove the support material. Operators can manually remove break-away support systems (BASS). To remove soluble support materials, operators must submerge parts in a chemical bath or a solvent, such as water or sodium hydroxide, which easily dissolves the support material.

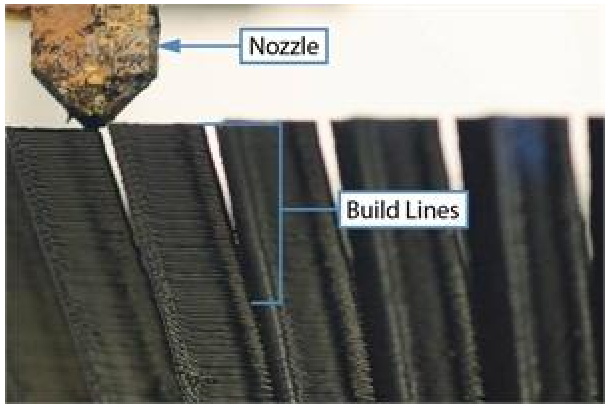
Early material extrusion machines exclusively used thermoplastics, a group of polymers, as build materials. Thermoplastics melt or soften easily when heated and retain their desired shape upon cooling. There is a large and diverse body of thermoplastics available for use in material extrusion systems. Common material extrusion thermoplastics include acrylonitrile butadiene styrene (ABS), polycarbonate (PC), polyamide (PA), and polylactic acid (PLA).

Many modern material extrusion machines still rely on thermoplastics, usually in the form of pellets or filaments, to build parts today. Due to recent technological advancements, however, material extrusion systems can also use a variety of other materials. For example, some material extrusion machines can use certain paste-like materials, such as ceramics or composites, to build a part. Other machines can even build products using biomaterials, such as living cells or tissue, or using edible materials, such as chocolate.



Material extrusion can create colorful polymer parts.

Material extrusion offers several advantages. For example, it is a relatively efficient method, and thermoplastic build materials are both inexpensive and readily available. Thermoplastics also offer an array of mechanical properties, physical properties, and optical properties. Manufacturers can use different property combinations to create parts with a variety of colors and uses, including prototypes and final end-use products. Additionally, material extrusion systems are widely available and typically easy to operate. They can build parts with greater geometric complexity and a variety of features that would otherwise be difficult, if not impossible, to make using traditional manufacturing processes.



Depending on the nozzle diameter, build lines may be visible.

Despite its advantages, material extrusion also presents certain disadvantages. For example, material extrusion parts often have visible build lines, so they suffer from a poorer surface finish than parts produced using other AM methods. While material extrusion systems can improve deposition rates using larger diameter nozzles, they produce less accurate layers and more clearly visible build lines than smaller diameter nozzles. In order to improve surface finish and reduce build line visibility, material extrusion parts often require additional finishing processes, such as sanding. Higher resolution parts often require more time to build, which results in lower build rates, or production rates, and can decrease the efficiency of the process.

1. The size of the extrusion head often determines how visible the build lines are for a part made by material extrusion.

✔ (●) True ( ) False

2. Material extrusion builds parts by selectively depositing adhesive material onto thin powder layers.

( ) True (●) False

3. Build materials for material extrusion include ceramics, composites, and biomaterials.

(●) True ( ) False

4. Material extrusion can build parts using metal filaments or wire.

( ) True (●) False

5. Material extrusion uses support materials to build parts with disconnected features.

✔ (●) True ( ) False

6. Parts made with material extrusion often have better surface finishes than other AM-produced parts.

( ) True (●) False

Directed energy deposition (DED) uses focused thermal energy, such as a laser, to melt and fuse materials in order to create a part layer.

During directed energy deposition, a deposition head focuses and directs thermal energy at a base, such as a substrate or build platform. The deposition head also contains nozzles that feed build material into the thermal energy. When the energy source and build material contact one another at the base, a melt pool forms. As the deposition head moves across the base in the shape of the desired part, the melt pool travels with it, creating a material layer that gradually solidifies upon removal of the energy source. Like material extrusion, DED creates parts by repeatedly passing over the base to build up layers of material.

DED encompasses several processes that all function similarly but use different thermal energy sources. For example, electron beam additive manufacturing (EBAM) uses an electron beam, laser-engineered net shaping (LENS) uses a laser, and direct metal deposition (DMD) uses a laser or plasma arc.

DED systems most frequently mount the deposition head on either a robotic arm or a motion system, which allows the head to move along multiple vertical and horizontal axes. DED systems surround the build area with an enclosure, which can fill with an inert shielding gas to prevent build materials from oxidizing

DED systems are able to build parts using only one build material or a combination of two or more build materials. The most common build materials for directed energy deposition are metals, such as stainless steel and titanium, as well as cobalt chrome and other superalloys. These metals are in the form of wire or powdered feedstock.

Manufacturers create metal powders using an atomization process. The type of atomization process used affects the metal powder quality. For example, water atomization produces lower quality metal powders that are tough, irregularly shaped, and have a relatively high impurity content, while gas atomization produces higher quality spherical metal powders that are more uniform in size and shape and have a lower impurity content. Unlike other AM methods that use metal powders, DED can utilize the lower quality metal powders produced by water atomization. Doing so, however, may often result in finished parts that fail to meet their specifications. Furthermore, while DED powder processes are generally more efficient than those using metal wire, they are often less accurate and produce more waste than metal wire DED processes.

DED possesses unique capabilities and benefits, particularly for repairing tooling or adding features to pre-existing objects. For example, directed energy deposition can repair damaged turbine blades or reinforce parts with a wear-resistant coating. Other parts that DED can build or enhance include aerospace components and medical implants.

DED also enables researchers to efficiently experiment with combinations of alloys and other materials. For example, researchers can find an ideal material blend for a part while producing less waste than traditional manufacturing. Using multiple material combinations also allows for the production of parts with material and property gradation.

Despite these benefits, DED is less accurate than other AM methods, and it does not easily accommodate the use of support structures. As a result, parts with disconnected features often require a considerable amount of planning prior to starting the build. Some DED parts, especially those built using the LENS process, often suffer from poor surface finish. Additionally, when using DED to repair a part, the newly deposited material may have a different microstructure than the original material. To improve surface finish and ensure DED parts have consistent properties, they often require heat treatment and other post-processing, which can considerably lengthen production rates.

Material jetting, or multi-jet modeling (MJM), works similarly to two-dimensional (2D) inkjet printers. However, rather than printing 2D images on paper with droplets of ink, material jetting builds 3D parts on a build platform with droplets of build material.

During material jetting, one or more print heads move horizontally over the build platform to deposit a layer of build material in the shape of a part. Most material jetting systems use thermoset build materials, such as photopolymers, but some can use wax build materials. Depending on the complexity of the part design, material jetting may also deposit wax as support material. Photopolymer build materials require exposure to ultraviolet light (UV light) in order to solidify. As a result, print heads often include an ultraviolet lamp (UV lamp), which flash cures the photopolymer material as it is deposited. Wax build materials, which do not require curing, cool after they are deposited. The build platform then lowers, and the print heads deposit a new material layer over top the first. Each layer solidifies and joins with previous layers. This process repeats until the part is complete.

Material jetting is a relatively fast and versatile AM method that offers several advantages. For example, material jetting systems can create AM parts with moving components, undercuts, and other complex geometries. The droplet layering process is highly accurate and capable of producing very thin material layers. As a result, a material jetting part usually has a higher resolution and smoother surface finish than other AM-produced parts. Additionally, because the materials cure and solidify during the build process, further post-processing curing steps are usually unnecessary.

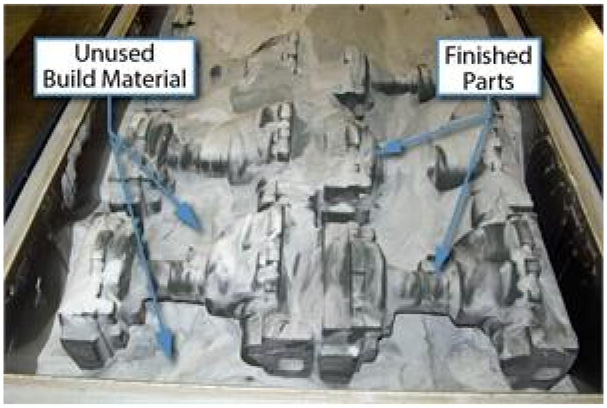
Most material jetting systems utilize more than one print head, which increases the number of different materials that a machine can simultaneously deposit and the number of different parts that it can build at one time. Some material jetting machines can mix two or more base materials together to create a composite build material that possesses the properties of each of the individual base materials. Varying the combinations of build material also allows for material jetting systems to produce parts with both color and property gradation.

Despite its advantages, material jetting still suffers from some specific disadvantages. For example, building complex part features requires support material. During post-processing, operators must remove support material either by hand or with a chemical solution, which adds time to a part's production rate. Furthermore, material jetting systems are limited to using only polymers and waxes, which are not as heat resistant or durable as the build materials used in other AM methods.

Binder jetting creates a part by depositing droplets of **liquid binder** onto a thin layer of powdered build material. During binder jetting, a **roller** spreads a layer of powder material over top a build platform within a **powder bed**. Print heads, similar to those used in material jetting systems, then selectively dispense binder droplets in the shape of a part over top the powder layer. The binder is an **adhesive** that **bonds** together the individual powder particles to form a part layer. Some binder jetting systems will apply heat or **pressure** over top the newly created part layer prior to dispensing a new layer of powdered build material. This process repeats until the part is complete. During the build process, the part remains in the powder bed, surrounded and supported by any unused powder.

Upon build completion, a binder jetting part is initially **green**, or very fragile. As a result, the part requires several post-processing steps. These steps include removing and recovering any unused powder, post-curing to fully harden the part, and using a specialized **infiltration** process that **seals** the part's surface, enhances its color, and improves its **strength**.

Binder jetting frequently uses polymer and metal powders. Common polymers include **PA**, **PC**, and **acrylates**, and common metals include stainless steel, **bronze**, and **tungsten alloys**. Some binder jetting systems can also use **foundry sand** to build **molds** and **cores** for **sand casting** processes.



Unused build material surrounds and supports binder jetting parts.

Binder jetting offers several advantages. For example, systems often utilize multiple print heads that quickly and simultaneously deposit binder agents. Using combinations of colored binding agents allows for full-color parts that also often have a higher resolution than some other AM-created parts. Additionally, binder jetting does not require support materials to build complex parts because the unused powder surrounding the part supports complex geometries. Finally, because manufacturers can recycle and reuse any remaining powdered build material, binder jetting is one of the most cost-effective AM methods.

Binder jetting parts often have a grainy surface finish. Photo courtesy of Hoosier Pattern.

Despite its advantages, binder jetting still poses some significant disadvantages. For example, while build lines on a binder jetting part are not as visible as some other AM parts, parts often have a grainy surface finish. This poorer surface finish coupled with the part's initial fragility results in a part that must be strengthened, hardened, and smoothed upon completion of its build and prior to use. Consequently, a binder jetting part requires several post-processing steps to improve its mechanical properties and surface finish. These additional processes also add a significant amount of time to the part's overall build time.

Powder bed fusion (PBF) uses focused thermal energy to selectively fuse layers of powdered build material. During powder bed fusion, a roller dispenses a layer of powder onto a build platform within a powder bed. An **image projection module** then focuses and projects the thermal energy, moving it in the shape of a part across the powder layer. Contact with the thermal energy fuses the powder particles together and forms a part layer. Afterwards, the roller dispenses a fresh layer of powder over the first, and the process repeats until the part is complete.

Most PBF systems use a powder bed that heats the build material to just below its **melting point**, which helps it fuse together more easily. Additionally, a **vacuum chamber** surrounding the entire build area fills with shielding gas to create an inert environment and prevent oxidation.

PBF processes include **selective laser sintering** (SLS), **direct metal laser sintering** (DMLS), **selective laser melting** (SLM), and **electron beam melting** (EBM). These processes differ based on their thermal energy source, their primary build material, and whether they **sinter** or melt the build material.

PBF Process	Thermal Energy	Build Materials	Sinter/Melt
SLS	Laser	Polymers, Ceramics, Composites	Sinter
DMLS	Laser	Metals, Metal Alloys	Sinter
SLM	Laser	Metals, Metal Alloys, Superalloys, Metal-Matrix Composites	Melt
EBM	Electron Beam	Titanium, Titanium Alloys, Cobalt Chrome	Melt

SLS, DMLS, and SLM often use **infrared** (IR) lasers as thermal energy sources, while EBM uses an electron beam. SLS can utilize a variety of powdered build materials, including polymers, ceramics, and composites. DMLS, SLM, and EBM use only metal powders. EBM is restricted to using only titanium, titanium-based alloys, and cobalt chrome. DMLS can use the powders of several metals and metal alloys. SLM, though, can utilize the greatest variety of metal powders including:

- Pure metals, such as titanium and **aluminum**
- Alloys, such as stainless steels, **tool steels**, and titanium alloys
- Superalloys, such as cobalt chrome, **Inconel**, and **nickel-based superalloys**
- **Metal-matrix composites** (MMCs) that are based on those metals

Finally, SLS and DMLS create parts by sintering and fusing material layers together, while both SLM and EBM fully melt powder particles, which creates a **homogenous** material layer.

The general PBF method as well as each of its individual processes possess specific advantages and disadvantages.

Powder bed fusion can quickly create batches of parts with fine details and consistent properties. Although some metal alloy parts may require heat treatment, most parts need minimal post-processing. Similar to binder jetting, most PBF processes do not require use of support structures since any unused powder in the bed surrounds the part and supports complex part features. Additionally, most of the leftover powder can be saved and reused in subsequent part builds as long as it is combined with fresh powder to offset the reused powder's **thermal degradation**.

PBF build materials may **warp** or **distort** due to **thermal stress** produced during the build process. Operators must carefully regulate **build parameters** during the build process. Build parameters include the temperature of the powder bed and **intensity** of thermal energy. For example, if the bed temperature is too high or the thermal energy is too intense, extra build material will melt and attach to a part. If the bed temperature is too low, however, a part will lose **density**. Low-density parts are often unreliable and may break if subjected to excess **stress**. Finally, due to costs associated with using vacuum chambers, PBF is more expensive than most other AM methods, such as DED.

SLS and **DMLS** usually produce parts with high quality surface finishes and details. SLS and DMLS parts are also often free from internal **defects** and possess good mechanical properties. However, SLS and DMLS parts often have high levels **surface porosity**, which requires post-processing steps, such as **sealing**, heat treating, or **hot isostatic pressing** (HIP). Additionally, DMLS requires the use of some support structures during the build process to prevent a part from significantly warping and distorting. Removing DMLS support structures often requires additional machining, which can make the process more time consuming.

By fully melting, rather than just sintering, build material, **SLM** is able to create a dense, strong part with a uniform composition. In fact, the density and strength of an SLM part often rivals those of traditionally manufactured parts. SLM typically builds parts faster than either SLS or DMLS. Nevertheless, SLM parts often have poorer **tolerances** and surface finishes than SLS and DMLS parts. Additionally, compared to DED processes, such as LENS, SLM is still a relatively slow process that is also quite expensive due to the amount of energy required to keep the build material at an elevated temperature.

Similar to SLM, **EBM** produces very dense, strong parts that are free of **voids** and possess excellent mechanical properties. Compared to laser-based PBF processes, EBM builds parts faster and exposes them to less thermal stress during the build process. As a result, EBM parts usually do not warp and distort as much as other PBF parts. However, similar to SLM, EBM parts often have poorer surface finishes and tolerances than SLS and DMLS parts. Additionally, EBM-compatible build materials, such as titanium, are both expensive and limited in availability. Material costs combined with costs associated with its technology and the specialized personnel required to run the process makes EBM somewhat more expensive than other PBF processes.

1. Binder jetting processes include selective laser sintering (SLS) and direct metal laser sintering (DMLS).

✖ ◉ True ○ False

2. Finished binder jetting parts often have a grainy surface finish, which requires post-processing to improve.

✖ ○ True ◉ False

3. Binder jetting deposits a liquid adhesive onto very thin layers of powdered build materials.

✖ ○ True ◉ False

4. Binder jetting requires the use of support structures.

✔ ○ True ◉ False

5. SLM and EBM are able to create a homogenous final part because they fully melt powdered particles.

✖ ○ True ◉ False

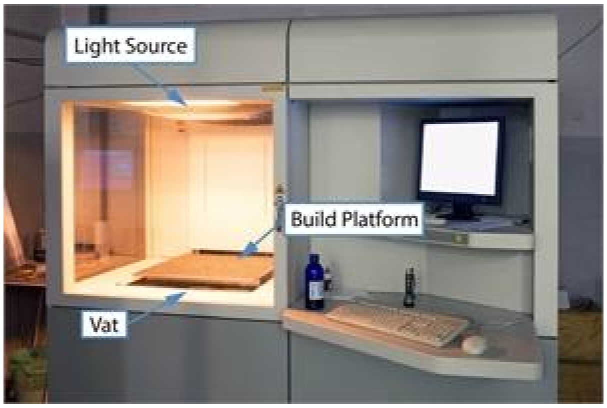
6. Powder bed fusion (PBF) uses focused thermal energy to melt and fuse materials as they are fed into a melt pool.

✔ ○ True ◉ False

Vat photopolymerization uses **light-activated polymerization** to selectively cure areas of a liquid photopolymer. Light-activated polymerization is a **chemical reaction** that hardens a photopolymer by exposing it to **radiation** from a **light source**, such as a **UV light**. During vat photopolymerization, light projects onto select areas of a **vat** of photopolymer. When the light's radiation contacts the photopolymer, it triggers the liquid photopolymer's **molecules** to cure and harden, permanently bonding them together to form a solid part layer. After a layer is complete, the system's build platform moves to allow a fresh layer of photopolymer to cover over the previous layer. The process then repeats until the part is complete.

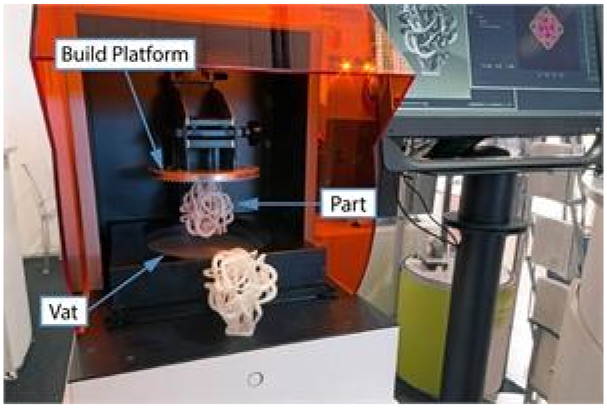
Vat photopolymerization includes several processes, some of which are **proprietary**. These processes differ in the way each projects light onto the surface of the photopolymer build material. For example, **stereolithography** (SLA), one of the first AM processes used in manufacturing, projects light from a **single-point source** onto the surface of the liquid photopolymer. The light moves in a precise pattern, tracing out the part's shape and eventually creating a solid part layer. Alternatively, **digital light processing** (DLP) uses a specialized **projector** that displays a part layer as an entire image onto the photopolymer. Upon contact with the projected light, the photopolymer cures and forms a solid part layer all at once.

Despite their process differences, all vat photopolymerization systems include the same basic components: a vat with a movable build platform, a light source, and a device that controls and directs the light. Light sources for vat photopolymerization include lasers, **light-emitting diodes** (LEDs), and electron beams. Vat photopolymerization-created parts often require several post-processing steps, such as removing supports or residual material in a chemical bath and curing parts in an **ultraviolet oven** (UV oven) to fully harden them.



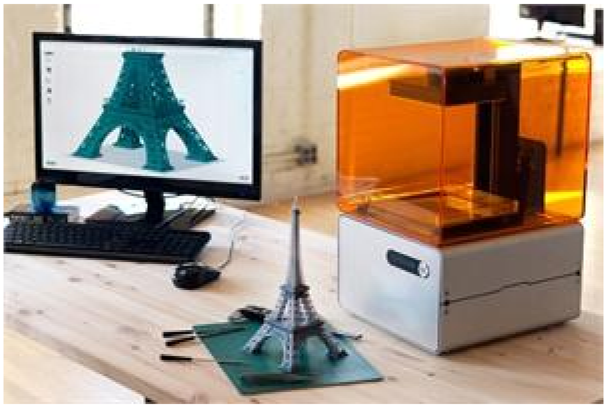
Top-Down Printing

Vat photopolymerization systems are oriented one of two ways. In **top-down printing** systems, the light source is directly above the vat holding the photopolymer build material, while the build platform is inside the vat. During the build process, an image projection module projects light downward onto the surface of liquid photopolymer in order to cure it and eventually create a part layer. Inside the vat, the build plate incrementally lowers upon the completion of each layer. A **recoater** then smooths a new photopolymer layer over the previous layer. Vats for top-down systems must be deep enough to contain the entire height of the part that is to be built. As a result, filling the vats requires a large volume of liquid photopolymer, which can be quite costly.



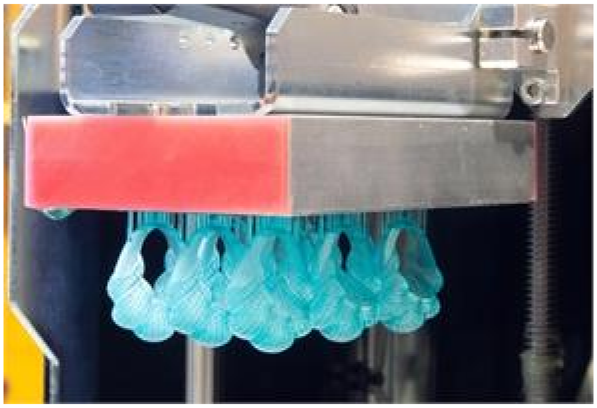
Bottom-Up Printing

In contrast, the vat is beneath the build platform in **bottom-up printing** systems. This vat is usually shallower and requires less photopolymer than a top-down system's vat. During the build process, the platform slowly moves upward, drawing the part out of the vat as each layer completes. Additionally, the light source is underneath the vat and projects light upward. In the vat's floor, an **optical window**, which is both **transparent** and **oxygen-permeable**, allows light and a small amount of **oxygen** into the vat. Oxygen prevents light-activated polymerization. As a result, a very thin **dead zone** forms directly above and adjacent to the optical window. The dead zone stops the photopolymer from curing and adhering to the optical window.



Vat photopolymerization machines are available in desktop sizes. Photo courtesy of Formlabs Inc.

Vat photopolymerization offers several advantages. For example, it is a highly accurate process that produces complex, detailed parts that often have high resolutions, close tolerances, and smooth surface finishes. There are a wide variety of photopolymer materials available. Some processes can also use photopolymer-based composites, which are typically a photopolymer liquid infused with ceramic powders. Composites allow for parts to be built with specific properties, such as increased hardness. Vat photopolymerization systems are available in a range of sizes, from smaller desktop systems to industrial-sized systems with larger build areas to accommodate large parts.



Parts made with photopolymer material often have less durability.

However, vat photopolymerization also poses certain disadvantages. For example, vat photopolymerization processes are relatively expensive, and their parts often require longer post-processing times than parts made by other AM methods and processes. Additionally, while numerous photopolymers are available, photopolymers are generally the weakest of all AM build materials. Photopolymers also often lack the stability and mechanical properties that other material groups have. As a result, parts built by vat photopolymerization are sometimes less durable than parts produced by other AM methods.

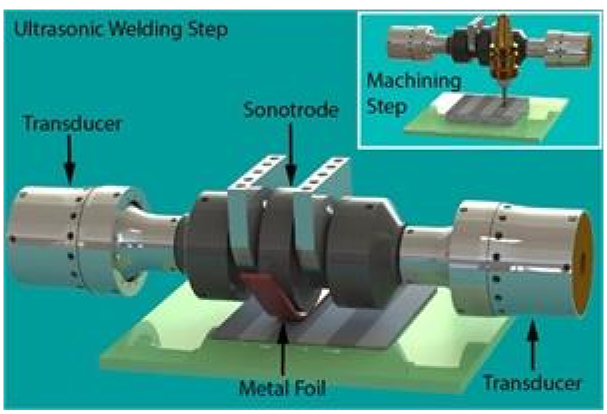
Sheet lamination builds parts by layering and bonding together thin sheets of build material. There are several sheet lamination processes, including **laminated object manufacturing** (LOM) and **selective deposition lamination** (SDL), both of which were among the first AM processes used in manufacturing.

During sheet lamination, a sheet of build material, usually paper, is fed from a feedstock roll into position over a build platform. A special roller applies an adhesive, heat, or pressure to the material sheet, and then a laser or a blade cuts the material to match the outline and **contours** of a part layer. Afterwards, the build platform lowers, and another material sheet is layered over and adheres to the first layer. Each step repeats until the part is complete.

LOM and **SDL** are ideal for creating **visual prototypes**, but other industrial uses for both processes are significantly limited. Complex geometries are difficult to create, and LOM and SDL are less accurate than other AM processes. Due to paper's limited properties, LOM and SDL parts have reduced functionality. Parts often require extensive post-processing to remove any excess material and finishing processes, such as **coating**, to prevent wear.

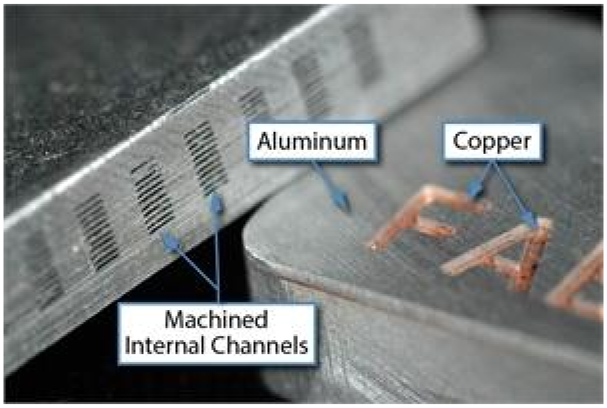
However, sheet lamination generally offers short build times, especially for large parts, and produces detailed, high-resolution parts in vibrant colors and with 100% density. Paper's low cost and availability combined with the ease of using and maintaining LOM and SDL systems also helps to make LOM and SDL the least expensive of all AM processes.

Ultrasonic consolidation (UC), or **ultrasonic additive manufacturing** (UAM), is a recently developed sheet lamination process that creates a part by fusing together layers of metal **foil** or tape. UC is a **hybrid process** that combines sheet lamination with **ultrasonic welding** and **subtractive manufacturing** processes, such as **milling** and **drilling**. Due to the hybrid process, a UC sheet lamination system includes a **mill** and **welding head**. The mill machines each layer of metal foil before the welding head fuses the layers together.

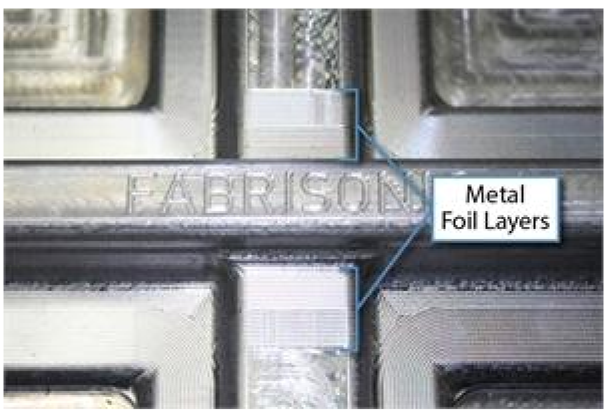


During ultrasonic consolidation, a sheet of metal foil is fed into position over a build platform. A mill cuts the metal foil to the **near net-shape** of the final part and machines any **internal channels**. Next, a second sheet of metal foil is fed over the first and also machined to near-net shape. The welding head, which consists of a **sonotrode**, or **ultrasonic**

horn, and two **transducers**, rolls over the metal foil sheet. The welding head vibrates at **frequencies** of around 20,000 **hertz** (Hz), creating a **solid-state weld** that joins the metal foil sheets together and produces a solid part layer. Before each welding head pass, the UC system must feed and machine a new metal foil sheet over the part layer. This process repeats, layer after layer, until the part is complete.



UC provides some unique advantages that make it ideal for certain industrial applications. For example, because UC uses vibrations instead of heat to weld the metal foil sheets together, it is an **ambient-temperature** process. As a result, manufacturers can use UC to produce metal parts with electrical components, such as wires or **sensors**, **embedded** between part layers. Additionally, the UC process is ideal for creating parts out of two or more dissimilar metals, such as **copper** and aluminum, which would be difficult, if not impossible, to accomplish using traditional manufacturing processes.

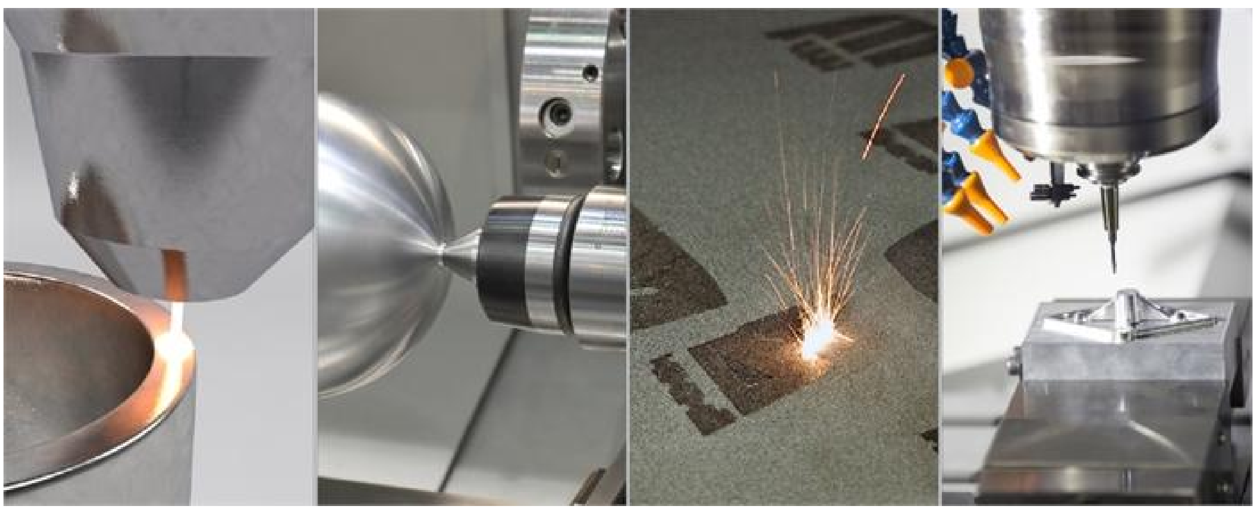


Despite its advantages, the UC process also poses some specific disadvantages. For example, finished parts are **nonhomogenous** and, therefore, not as strong or durable as some other AM-produced parts. UC is also limited in its ability to produce parts with complex geometries due to the machining processes required during the part build. Additionally, similar to both LOM and SDL, UC parts often require further machining along with additional post-processing and finishing to prevent wear, reduce build layer visibility, and improve a final part's mechanical properties.

An AM method that selectively cures liquid build materials by exposing them to light.	Vat Photopolymerization
An AM method that layers and bonds together thin pieces of build material.	Sheet Lamination
A process that traces a focused single-point source of light over the surface of a build material.	Stereolithography
A process that creates a part layer by projecting an entire image onto a build material's surface.	Digital Light Processing
A process that uses vibration to bond together layers of metal foil.	Ultrasonic Consolidation

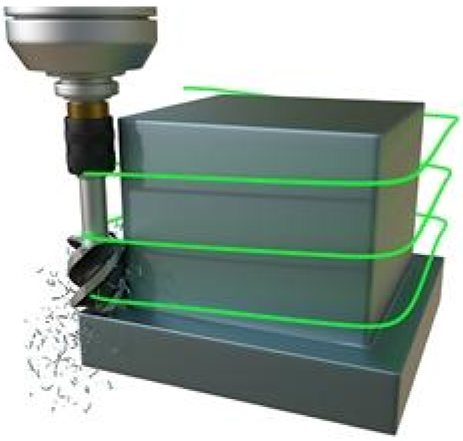
151: HYBRID MANUFACTURING

In order to create parts from **raw materials**, manufacturers often use **subtractive manufacturing** methods, which create parts using cutting tools to remove selected areas of material from a larger **workpiece**. However, **additive manufacturing** (AM) processes, which create parts by progressively adding or fusing layers of raw material into a solid shape, are becoming more common.



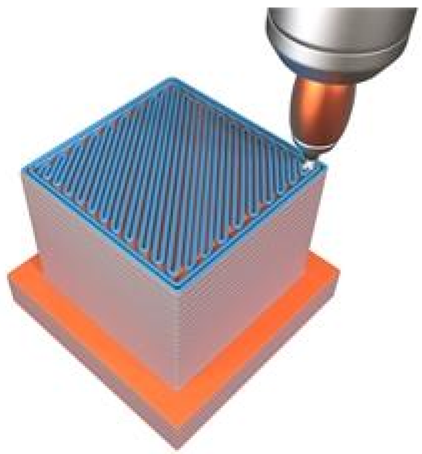
Design for both subtractive and additive manufacturing relies on **computer-aided design** (CAD) software. Additionally, while early subtractive methods could be done manually, today, part production with subtractive and additive methods relies on **computer-aided manufacturing** (CAM) technology. CAM typically prepares **digital** instructions for **computer numerical control** (CNC) software to control tool movements on a machine. These programmed tool movements cut or build a part based on a CAD model. CAD/CAM systems, combined with the enhanced digital connectivity of the **Industrial Internet of Things** (IIoT), allow manufacturers to streamline design and production workflows and also to combine processes in new ways. Harnessing digital networks to combine separate manufacturing processes into a single workflow is often called **hybrid manufacturing**. Most often, hybrid manufacturing processes combine additive and subtractive manufacturing methods into one process, which is sometimes called **hybrid additive manufacturing** (hybrid AM). While subtractive and additive methods have different advantages, both also have certain limitations. Many manufacturers use hybrid additive manufacturing to optimize part design and production in a variety of ways.

A hybrid additive manufacturing workflow combines the strengths of both additive and subtractive manufacturing methods.



Subtractive Process

A subtractive manufacturing process builds a part by removing material from a workpiece. Typically, designers use **CAD** software to create a part design, and an engineer uses **CAM** tools to convert the CAD model into a **part program**. The part program maps out **toolpaths** for cutting or finishing tools on a CNC machine. The CNC machine cuts the workpiece into the shape of the finished part based on the CAD dimensions. Subtractive processes can remove very specific amounts of material from a workpiece. This is ideal for making highly precise holes or other part **features** that must meet very tight **tolerances**, or for producing a high-quality surface finish. However, subtractive processes often create large amounts of waste as any workpiece material that the process removes becomes scrap. Additionally, CAD models for subtractive methods must account for workpiece and tool dimensions, cutting speed, depth of cut, feed rate, and many other factors.



Additive Process

An additive manufacturing process can build a part from scratch by fusing layers of material, such as melted plastic or metal powder. Like subtractive, most additive parts also begin with a CAD model. However, since additive processes build a single layer of the workpiece at a time, converting from CAD to CAM is easier to automate than with subtractive methods. This can eliminate the need for a skilled engineer to program complex toolpath sequences. **AM** also makes design **customization** easier because it is ideal for building complex geometrical shapes. However, since material is deposited in specific quantities, and melted material changes dimensions as it cools, additive methods cannot create precise holes or meet tight tolerances as effectively as subtractive methods. Additionally, AM processes are unable to produce parts with high-quality surface finishes.

Hybrid additive manufacturing may refer to various production workflows that apply subtractive and additive processes to a single part. However, simply applying different processes to produce a part is not enough to be considered hybrid manufacturing. A hybrid manufacturing process uses a combined digital workflow and also combines multiple processes at a single location.

Some **hybrid AM** processes may use separate additive and subtractive machines to complete a part, but these machines exchange digital information or share software on a digital network. Networked machines in a hybrid AM process may share CAD/CAM data, as well as data collected and analyzed by **smart sensors** on each machine in **real time**. This real-time data may be analyzed throughout the manufacturing process to eliminate unnecessary idle time on each machine and optimize the production workflow.

A **hybrid machining center** combines both digital and mechanical tools for additive and subtractive processes on a single, all-in-one machine. Like a traditional CNC machining center, a hybrid machining center consists of a large cabinet, a worktable, and an **automatic tool changer**, but hybrid machining centers can alternate between cutting tools and additive tools. Hybrid machining centers can create unique parts that could not be produced by separate machines since operators can use both tool types at any point without relocating the part. If a manufacturer plans to use both additive and subtractive technology, using a hybrid machining center may be more practical and cost-effective than purchasing CNC machining centers or CNC turning centers and AM machines separately.

However, hybrid manufacturing does not necessarily require the purchase of an additional machine. Many print nozzles are designed to be added to traditional CNC machines as **print head attachments** in order to convert subtractive machines into hybrid machines. Hybrid machine attachments may be practical for manufacturers looking to integrate additive capabilities into their existing operations.

Most all-in-one hybrid machines combine a metal AM process, usually **directed energy deposition** (DED) or **powder bed fusion** (PBF), with a **material removal** process. Directed energy deposition uses a print nozzle to dispense powdered material from a **material hopper** or wire material from a **material spool**. The nozzle also emits a **laser**, **arc**, or other thermal energy source that melts dispensed material into layers to build a part. In a typical hybrid DED process, once the print nozzle builds the part, cutting tools such as **mills**, **drills**, **turning inserts**, or **abrasives** are then used to complete the part so it meets **design specifications**. Powder bed fusion most often uses a laser to heat and fuse layers of **powdered metal** or other powdered material together to build a part. As each part layer is completed, the **build platform** supporting the part sinks lower into the powder bed until all layers are complete. In hybrid applications, PBF is combined with machining tools such as drills, end mills, or face mills. Typically, PBF builds one or more layers of the part, then a machining tool trims the finished layers to specifications before the part is lowered and the PBF laser fuses the next layer.

Rather than using DED or PBF, some additive hybrid processes may use **ultrasonic additive manufacturing** (UAM), a type of **sheet lamination**. UAM is an additive process that bonds together thin sheets of metal using **ultrasonic** waves. In UAM, as a sheet of metal is pressed against a metal base or other sheet of metal, ultrasonic vibrations create friction that causes the metal to bond together in a solid state. In hybrid UAM applications, once the metal is bonded, a cutting tool cuts the metal layers to design specifications. While UAM can be ideal for solid-state bonding of multiple metals, it does not typically provide the same level of complex geometry as hybrid DED and PBF methods.

1. Directed energy deposition (DED) is one of the most common additive manufacturing methods used in hybrid manufacturing processes.

- (●) True ( ) False

2. Hybrid all-in-one machines can produce components that would be impossible to produce using separate additive or subtractive machines.

- (●) True ( ) False

3. Hybrid sheet lamination processes can easily create more complex part dimensions than hybrid directed energy deposition (DED) processes.

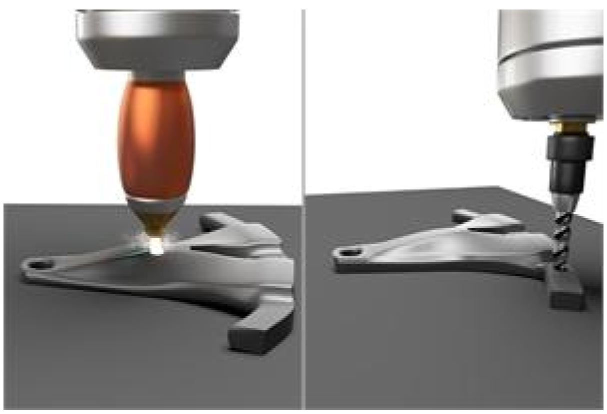
- ✔ ( ) True (●) False

4. Hybrid manufacturing processes provide less precision and accuracy than traditional subtractive manufacturing methods alone.

- ( ) True (●) False

5. A hybrid machining center can eliminate the need for separate additive and subtractive manufacturing machines.

- (●) True ( ) False



In most hybrid AM production workflows, a machine builds a **near-net shape** workpiece using an additive process, such as **DED**. Next, once the workpiece is built, a subtractive process, such as CNC **machining** completes the part. However, additive and subtractive processes may also be alternated throughout the build process to create unique part features.

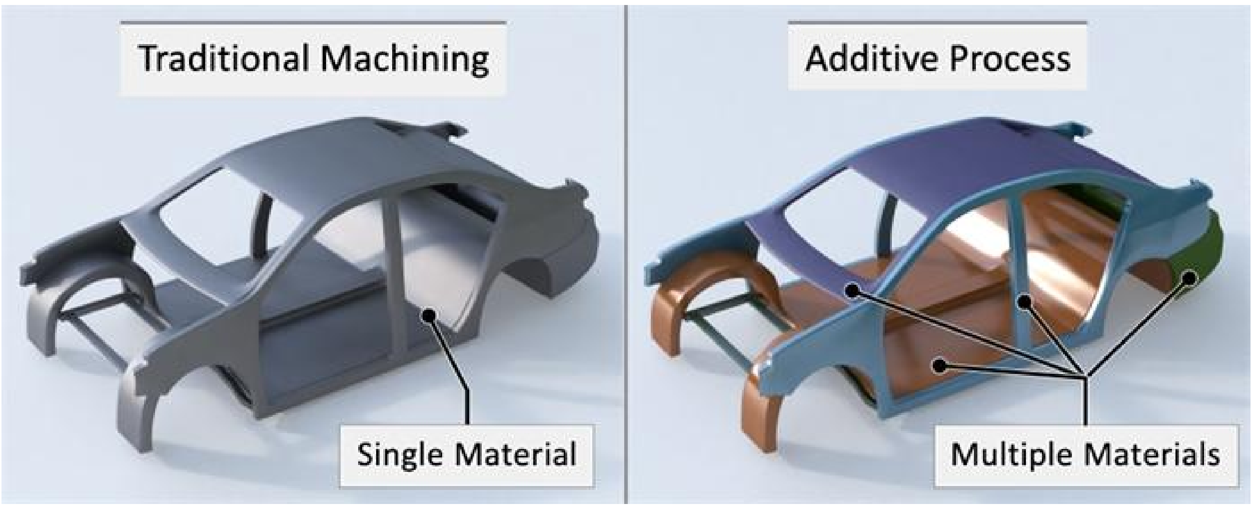
Alternatively, rather than building the entire workpiece with additive methods, a hybrid AM workflow may start with a **forming** process to create a **casting** or **forging**, then use an additive process to complete the part. Castings and forgings are **net shape** or near-net shape parts created by a **mold**. Since additive processes can be time consuming, using castings or forgings for the part base can greatly reduce production times. AM tools can then apply additional materials to create final part features or apply high-performance, and often expensive, materials in specific areas to optimize performance and save costs. Typically, this hybrid AM workflow also uses a finishing process to improve surface quality of the completed part.

Hybrid AM processes may also begin with subtractive methods on a **billet** of material, then use additive methods to complete the part. For example, a marine manufacturer may use cutting tools to machine a boat propeller shaft to specified dimensions, then complete the propeller by building the blades on the shaft with a DED nozzle or other AM tool.

The overall advantage of hybrid AM is that it combines the design complexity and reduced material costs of AM with the superiour accuracy and surface finish of subtractive methods. Material costs can be reduced using an all-in-one hybrid machine or using separate additive and subtractive machines, but using separate machines can slow production since parts and materials must be transferred between steps. A hybrid AM machine, however, does not have this disadvantage and greatly improves production efficiency. All-in-one hybrid machines and hybrid AM machine attachments can have high up-front costs and may require additional training for personnel. However, manufacturers often consider the **total cost of ownership** (TCO) when comparing hybrid AM machines to traditional production methods. The TCO includes equipment, labor, time, and other costs related to owning particular machines or equipment. A hybrid AM machine reduces TCO over the long term.

In addition to reducing production times, hybrid AM machines allows manufacturers to automate the additional inspection steps often required when using AM methods. AM typically requires multiple inspection steps throughout the build process to adjust for defects or inconsistencies in the build. For example, when creating a near-net shape part with AM, technicians may need to inspect the part before it is completed to verify that part dimensions are accurate based on the CAD model. Automating inspection on a hybrid AM machine using probes, laser scanners, or other methods optimizes inspection times, significantly improves quality, and reduces part defects.

All-in-one hybrid machining centers and hybrid machine attachments allow manufacturers to design and produce components that could not be produced otherwise.



Advances in hybrid AM allow more complex and accurate builds from multiple materials.

Alternating between additive and subtractive processes on one machine allows manufacturers to produce unique part features while also improving the precision of each feature. Additionally, hybrid AM machines can finish deep or internal part features, such as internal holes or pockets, during the build process before external part features block access to these surfaces. AM tools on hybrid AM machines also allow manufacturers to design and build components made up of different layered materials. For example, adding a layer of copper improves **electrical conductivity**, and adding small quantities of high-performance metals, such as **superalloys**, improves hardness or other properties. These AM tools can greatly reduce material costs since expensive materials are only used where needed. Combining AM tools with cutting and finishing tools allows hybrid AM machines to produce highly accurate parts with unique properties at a lower cost than traditional methods.

Hybrid AM processes can produce innovative new devices that are highly customized. For example, a manufacturer can use AM to produce complex parts like prosthetic limbs or dental implants, then machine the parts down to highly precise, personalized dimensions. This can improve functionality and overall performance of the medical device.

Equipment for the **aerospace** industry often requires highly customized parts and components. Aerospace parts are typically produced in small **lots** and must meet very high tolerances. Hybrid AM processes allow manufacturers to produce these very precise custom parts within required tolerances. These parts often require superalloys and other expensive metals, and hybrid AM processes help reduce material costs by reducing waste. This can help aerospace part manufacturers meet high quality standards while improving **lean manufacturing** and other waste management practices.

Traditional AM methods can produce customized tooling, such as custom robot **grippers** or a custom mold for a part casting. With AM, manufacturers can design custom molds that use **conformal cooling** channels rather than conventional channels made with subtractive processes. Hybrid AM allows manufacturers to produce custom molds with conformal cooling that are also highly precise. Producing custom molds on a hybrid AM machine can improve **repeatability** and increase production volume. In addition, hybrid AM machines can also reinforce the mold cavity surface with a single layer of specified metal or other material that may help the part casting cool and solidify faster or provide other benefits.

Repair and maintenance operations can also combine custom molding with both additive and subtractive processes to repair damaged parts and components more accurately. In many hybrid AM repair processes, the manufacturer creates a mold of the damaged part, then uses a DED nozzle to rebuild the part component from the mold. Once the replacement part component is built, subtractive processes, such as grinding, may bring the replacement component to final quality specifications.

161: RAPID PROTOTYPING

Additive manufacturing (AM) is a newer manufacturing process that builds **three-dimensional** (3D) objects by adding one layer of material at a time. There are a variety of AM methods that use a number of different materials such as plastic or metal. In contrast, most traditional manufacturing processes are subtractive, as they remove, or subtract, pieces of a material in order to create an object or part.

Today, AM methods, which may be referred to as **3D printing**, have many applications in manufacturing including the creation of functional end-use products. However, AM began in the 1980s with **rapid prototyping**, a process of quickly creating prototypes to test designs and support new products in traditional manufacturing. Since those early days, rapid prototyping techniques have expanded to include a wide variety of AM methods and materials. These AM techniques enable manufacturers to create lighter and more complex AM prototypes and end-use products without sacrificing quality.

Conceptualization refers to the formation of an idea about a possible part or product. It represents the initial design stage for manufacturing.

The **planning** stage involves figuring out the best way to create the initial design, or concept. Planning considers how an innovative concept might fit together with the practical concerns related to manufacturing processes.

The **designing** stage begins with the process of creating the actual specifications for a prototype or potential part. Developing a prototype can include such things as creating a **blueprint** or digital model with **computer-aided design** (CAD). Rapid prototyping is the process of using AM operations to create prototypes for parts that will then be produced through traditional manufacturing.

The **testing** stage examines a part prototype to ensure that it performs its designed function when manufactured. Testing can indicate if a part is ready for production or needs additional planning and designing.

The **production** stage represents the final stage of design in manufacturing design. The production process creates the tested design and delivers it to a customer as specified.

Planning, designing, and testing represent the steps most associated with the development of a **prototype**, the preliminary model of a part used to evaluate the performance and **functionality** of a design. Effective prototyping ensures the manufacturability of the part during the production stage.

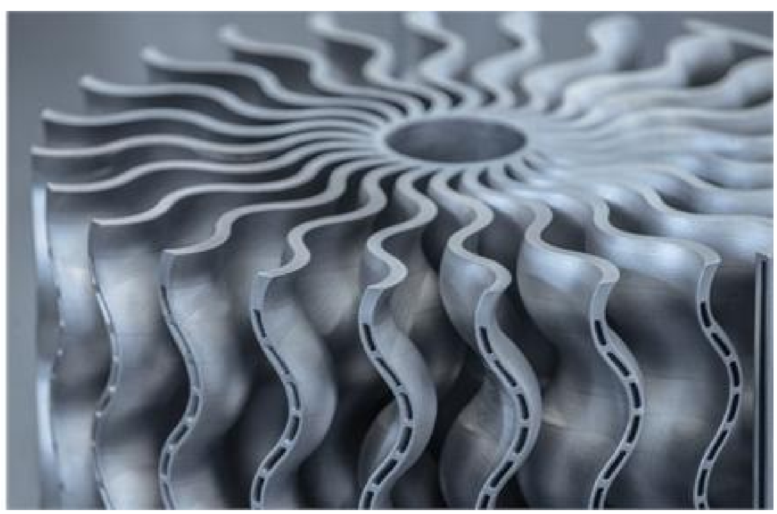
CNC mill creating a grooved surface.

Prototyping for traditional manufacturing has limitations based on the **raw materials** available. For example, **bar stock** can come in round, rectangular, and square set forms which have limits as to how tools can reshape the material. The tools used to shape the materials also have limits. For example, a **computer numerical control** (CNC) **mill** can create excellent flat or grooved surfaces, but has difficulty creating more complex part shapes. Using subtractive manufacturing processes like CNC machining for prototyping also requires a different machine and tool **setup** for each prototype, which is time consuming and expensive.

Complex topology of an AM part.

Unlike traditional manufacturing, AM prototyping does not require machine reconfiguration and retooling, which can greatly shorten the planning, designing, and testing steps. This enables manufacturers to focus on the capabilities and complexities of a prototype. For example, AM prototypes can create lighter, stronger, and more complex parts for aircraft, which leads to better performance and lower operating costs. Although AM offers more flexibility with materials, AM machines can typically process only one category of material at a time. For example, **direct metal laser sintering** (DMLS) can only create metal objects. In addition, unique challenges associated with AM prototypes include the use of a **support structure** and issues with **topology**, or the ways in which geometric or material shapes get arranged in a part.

Originally, all AM processes were used exclusively for rapid prototyping.



AM rapid prototypes are often **conceptual models**, which are non-functional part prototypes that allow designers to provide a physical example of their design ideas. Conceptual models may be made at a smaller size or out of a less expensive material than a functional part in order to save time and costs, especially if the design is likely to change and require additional prototypes. For instance, aircraft manufacturers might use additive manufacturing to create a rapid prototype of a new aircraft turbine wheel designed to maximize air flow. The conceptual rapid prototypes may look like a turbine wheel but built smaller or made of lower-cost material like plastic or foam. A conceptual prototype can help communicate the part design and structural requirements to management, production personnel, and others involved in determining whether or not a part design is feasible for production.

Engineers also use rapid prototyping to create a **functional prototype**, which are prototypes that match every specification of the part like size, material, and weight. Functional rapid prototyping allows for **iterative design**, or trying and testing different variations to a part before putting it into full production. In the turbine wheel example, an engineer can use AM to produce multiple fully-functional turbine wheels with slight variations to their design and subject them to rigorous testing. The testing produces data that can help determine which design performs best. Using traditional manufacturing methods, such as CNC **machining**, would require much larger amounts of the expensive materials used to create aircraft turbines. By combining rapid prototyping methods with iteration, businesses can save costs without sacrificing performance and quality.

1. AM prototyping requires machine reconfiguration and retooling.

   ○ True ● False

2. Additive manufacturing machine turns a digital model into a physical object by joining or fusing layers of material.

   ● True ○ False

3. Conceptual rapid prototypes may look physically identical to a part but lack its functional qualities.

   ● True ○ False

4. The production stage examines a part prototype to ensure that it performs its designed function.

   ✔ ○ True ● False

Similar to traditional CNC machining, in the first step of rapid prototyping an engineer creates a part model using **CAD** software. An engineer typically creates a 3D model of the part because it is more accurate than a traditional **two-dimensional** (2D) drawing. This generates better outcomes during testing.

After completing the 3D design, the engineer then converts the CAD model to a **stereolithography** (STL) format. Engineers use STL files for all rapid prototyping processes because of the software's compatibility with AM machines. Converting a CAD file into an STL file converts the 3D model into a sequence of interconnected triangles.

Most AM machines cannot read STL files. Therefore, software must convert the STL file into **G Code**, a numerical control programming language that a digital slicing program will understand. The digital slicing prepares layers of material that the AM machine will fuse or dispense as it builds the prototype.

The rapid prototyping process, like any additive manufacturing process, is typically automated. Once completed, however, the model may need cleaning or **finishing**. Also, any support material used in building the model must be manually detached or removed during **post-processing**.

Rapid prototyping has many common applications. The automotive, aerospace, and other transportation industries use rapid processes for **lightweighting**, in which engineers design vehicle components with the goal of getting the lightest weight possible for the required strength. Lightweighting can involve swapping out traditional materials for lighter ones or creating normally solid parts with internal **lattice structures** or **honeycomb structures**. For example, by replacing glass windows with plastic or metal bumpers with carbon fiber, vehicles can achieve better gas mileage without sacrificing safety.

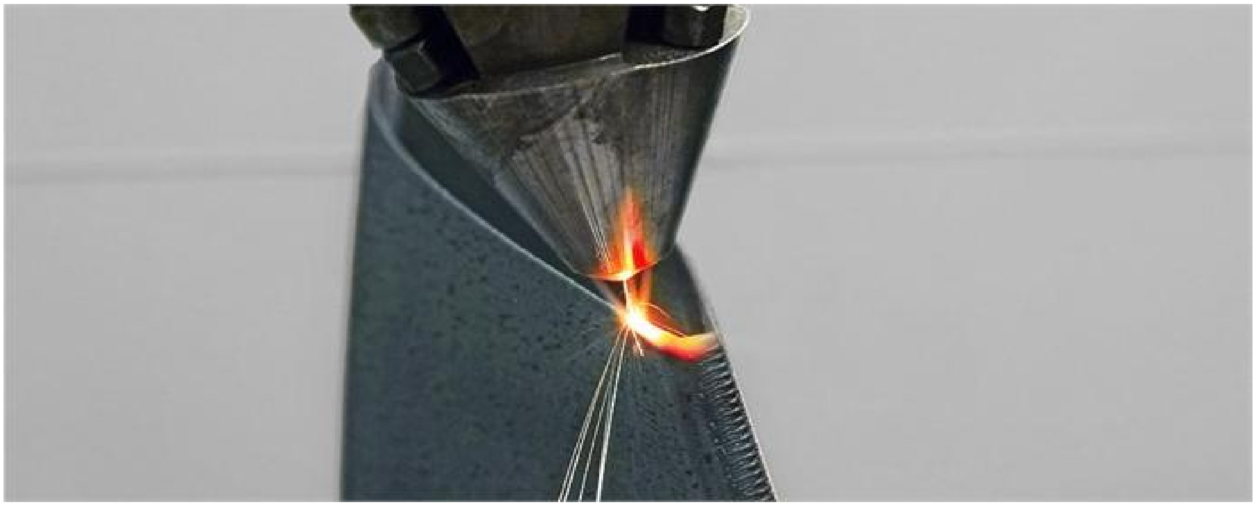
Rapid prototyping allows manufacturers to test part design with a less-expensive material than the actual part would require, which helps reduce costs. In some cases, this can also include rapid prototypes of tooling. For parts made using a **mold**, engineers can substitute **hard tools**, or molds made from metals such as aluminum or steel, with **soft tools** made from less expensive materials such as **silicone**. For example, using additively manufactured silicone molds for prototyping is more economical than creating metal molds for shorter production runs. Soft tools generally get the same results as hard tools. However, soft tools may only have a quarter of the lifespan of traditional hard tools, so hard tools are more economical for larger production runs. .

Advances in rapid prototyping depend on the combination of **hardware**, software, and materials working together. Improvements to this process strive to optimize such things as build times, material preparation, and complexity. For example, newer AM software can work with existing STL files to create more complex lattice structures or innovate with new **multimaterial gradients**.

Manufacturers may choose to keep prototyping within their organization, or they may **outsource** to a third party that specializes in rapid prototyping. Advantages to creating prototypes in-house may include quicker turnaround times. Third-party prototyping operations may take over a week, including transporting. However, a physical prototype can potentially be made in-house and consumer-tested all in the same day. In-house prototyping also provides greater security against **intellectual property** (IP) theft, as digitally transferring CAD or STL files poses **cybersecurity** risks.

Some disadvantages to in-house rapid prototyping can include significant up-front costs. In-house AM requires purchasing materials and machines, and can also involve the time and cost of training staff and regular machine maintenance. Using a third-party rapid prototyping company avoids up-front costs, but is more expensive if used regularly. However, third party rapid prototyping companies may provide more options for production processes and materials than an in-house operation.

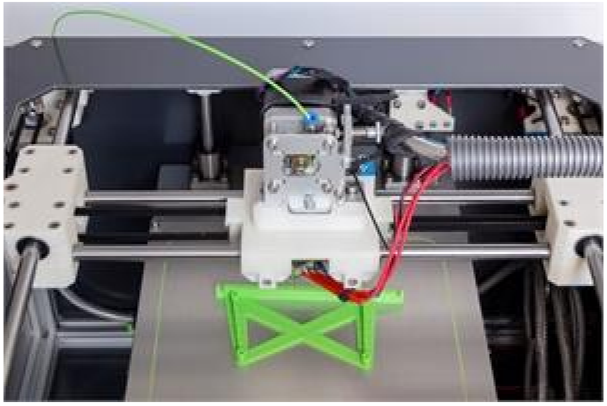
162: Additive manufacturing: prototype to production



Additive manufacturing (AM) includes multiple processes that build parts by fusing layers of **raw material**. Although it is typically associated with **rapid prototyping**, a growing number of manufacturers are working with AM to create **end-use** products and **near net-shape**, or near-finished parts. End-use is a term used to describe parts and products used directly by the consumer. These includes things like custom medical equipment, such as **prosthetics**, and **printed circuit boards** (PCBs) for electronics. Manufacturers can also use AM for repairs, such as filling cracks or holes in existing parts.

Increasingly, AM processes are being combined with traditional methods to create **hybrid manufacturing**, which builds a completed part with greater efficiency. In some cases, a manufacturer may use AM to make customized **fixtures** and **jigs** for traditional processes. Additionally, utilizing AM techniques to make small-batch lots can save manufacturers the cost of creating tooling, workholding, and automation for limited-run parts. Using AM processes for production may have some disadvantages, but compared to traditional methods, AM has proved to be more agile for meeting customer demands.

AM production represents a diverse field of materials and processes. Traditional manufacturing generally uses subtractive processes, such as **milling** and **turning**, to remove selected areas from a piece of raw material in order to create a finished part. In comparison, AM processes build parts by joining materials together, layer by layer, based on a **three-dimensional** (3D) computer model. There are many different additive manufacturing methods.



Directed energy deposition (DED), **material extrusion**, and **material jetting** use a device such as a nozzle to deposit build materials

Vat photopolymerization directs an **ultraviolet** (UV) light to cure selected layers of specialized **resins** to form parts.

Sheet lamination bonds sheets of material together using heat or other means, with a feed roller.

Powder bed fusion (PBF) and **binder jetting** processes bond selected areas of material in a powder bed. Each of these methods also includes variations, which are often based on the build materials. For example, binder jets may use metal powder to make stainless steel parts for airplanes or ceramic powder to create parts like a high-pressure turbine nozzle.

Additive manufacturing eliminates many of the limitations of traditional **machining** processes that subtract or remove material. Subtractive machining requires a different machine **setup** for every part or prototype, which can take a significant amount of time to change. Machining is also limited to the shape of the raw material and the abilities of a tool. For example, a facility may need to create a part that requires two components to meet at a 90° angle. Using a machining process would require either removing and wasting a large amount of material between the components, or creating them separately and using a **joining** process like welding, which would add a large amount of time to the part production process. AM production can reduce waste by building the angled part in one piece, using only the necessary amounts of raw material.

In rapid prototyping, AM can also enable manufacturers to quickly create **iterative design** prototypes that focus on functionality. These prototypes can have varying material compositions layer by layer, or **material complexity** and allow for **hierarchical complexity**, which lets a multi-scale part transition from simple to complex shapes as it is built. The ability to quickly create many test versions of a part enables manufacturers to meet customer demands with greater speed and agility compared to traditional processes. For example, an aircraft manufacturer may need to quickly develop a new type of duct component to prevent a front windshield from fogging up and impairing pilot visibility. Using a **PBF** process like **direct metal laser sintering** (DMLS), they can rapidly create and test multiple prototypes to **customize** the end-use part to meet the unique design needs or to meet strict aircraft requirements. They can then use the same DMLS process to create the end-use part.

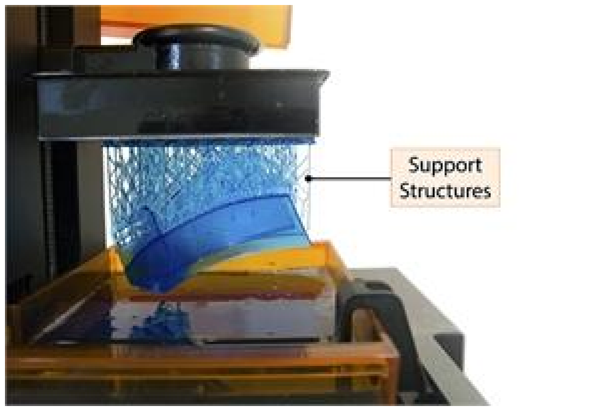
Traditional Processes: Drilling and Welding

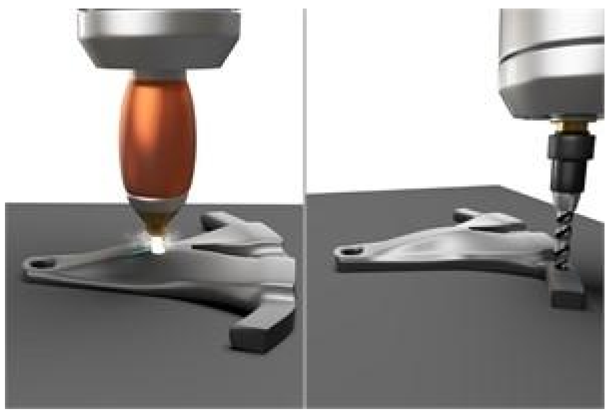
Additive Process: Directed Energy Deposition

Adopting additive manufacturing requires significant up-front investments in machines and materials, though the **total cost of investment** can be lower than traditional manufacturing due to reduced material, setup, and other costs. Working with AM can also require specialized, multi-functional training. For example, an operator building **thermoplastic** components using material extrusion must understand the material they are working with, the material extrusion process, and machine maintenance requirements such as cleaning extrusion nozzles. Similarly, operators must understand that AM processes that produce low-strength parts may not be appropriate for building structural components like a **bracket** for a door latch.

End-use products made with additive manufacturing may also need **post-processing**, or extra steps, before they are completed. These extra steps can lower **build rates**, or the number of parts made during a set period. For example, some AM parts require **support structures** to support the part during building, and personnel often need to remove these structures manually. In other instances, meeting the precise design size and **specifications**, or **dimensional accuracy**, for an AM part may prove challenging. To compensate, a manufacturer may need to use subtractive post-processing to drill a hole or grind a smooth surface finish.

An increasingly common method of avoiding the disadvantages of both additive and subtractive processes is hybrid manufacturing. Hybrid manufacturing combines AM with traditional **computer numerical control** (CNC) machines, either by creating a specialized hybrid machine or by adding an AM nozzle to an existing CNC machine. Hybrid processes allow manufacturers to create some part features using AM and others using traditional machining without needing multiple machines or setups.





Hybrid Manufacturing

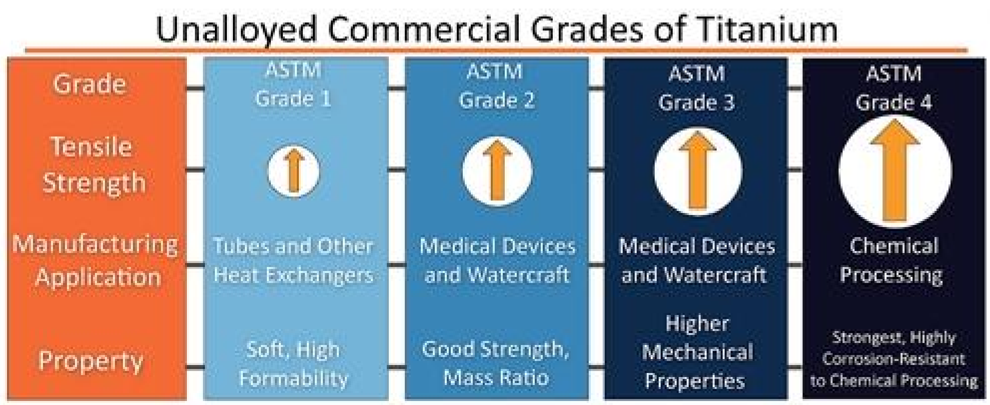
Because AM includes a wide range of machines and processes, companies using additive manufacturing have great flexibility in their production strategies.

A complex product may consist of a few AM components among traditionally made products. For example, an automaker may use **fabrication** processes to create the majority of a car door but use AM to make a window guard rail that is difficult to produce with traditional methods.

AM is ideal for creating custom medical equipment and devices. Additive processes are commonly used to make devices including hearing aids, prosthetics, and dental products. Manufacturers also use AM processes to make different kinds of **orthopedic** implants for the spine and other areas of the body.

AM used for small-batch part lots can be cost effective, since additive manufacturing processes do not require different setups for each part lot and may prevent needing to use multiple processes. For example, using AM may save manufacturers from making non-standard tooling and workholding devices to create a small number of customized parts.

Uses for additive manufacturing are growing every day as the technology evolves. For example, laser additive technology is used to repair cracks in metal components. In addition, manufacturers can also use AM to make custom tools that assist with traditional manufacturing. These can include things like a fixture to hold parts securely or a mold used to shape a specialized part.



AM methods use a variety of materials. The most typically recognized AM process is **3D printing**, which is generally material extrusion using plastic **resin** as the raw material. However, AM processes that use metal, like **DED** and PBF, are common for industrial production. Other popular materials used in additive manufacturing include **polylactic acid** (PLA), ceramics, and **nylon**.

During the evolution of AM technology, many AM developers used their own terms and standards, which caused confusion. The **International Organization for Standardization** (ISO) and the **American Society for Testing and Materials** (ASTM) work together to create a framework of unified standards to ensure all AM business products have the same high quality worldwide. The AM specifications for creating certain metal **grades**, or categories, of **titanium** and **aluminum** is one of the more important standards created by the ASTM/ISO collaboration. For example, these grades can provide guidelines for AM manufacturers who build castings for surgical implants or dental restorations. The unified set of standards enables manufacturers to communicate better with each other. In turn, this ensures that anyone using an additively manufactured product, whether as a passenger on an aircraft or within their own body, can trust the product's quality.

AM end-use products can require different **inspection** methods than traditional manufactured parts because they are built differently. For instance, many AM parts may have more complicated internal structures compared to traditional parts, which are often machined from solid pieces of raw material.

Manufacturers inspect parts to prevent serious **defects**, or flaws that prevent a part from meeting **specifications** for a part. **Destructive testing** and **nondestructive testing** represent two methods of inspecting parts for defects. Destructive testing includes taking a random sample from a production line and inspecting it in a way that breaks or damages the part, which turns it into scrap. For example, a manufacturer using AM techniques to mass produce a part may use **tensile testing**, which stretches the part until it breaks, to determine its strength. Nondestructive testing includes inspection methods that do not damage a part or its future usability. For example, a manufacturer may decide to use a nondestructive testing method like **ultrasonic inspection**, which uses sound, or **x-ray testing**, which uses light.

Not only can storage and handling affect the quality of the built part, but it can also impact production times. In addition, AM techniques using metal must maintain the quality of the powder to consistently grade quality standards set forth by **ASTM** and **ISO**.

Destructive Tensile Testing

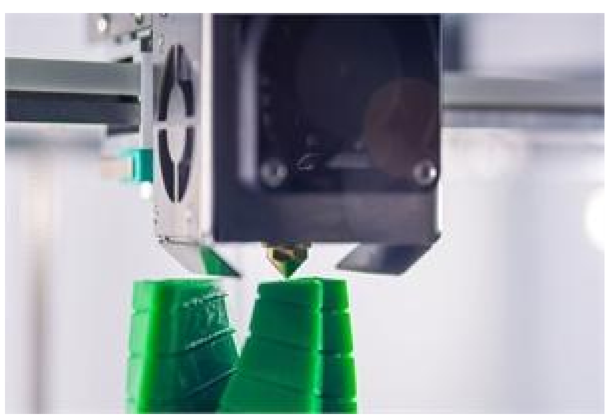
Nondestructive X-Ray Testing

201: Design for Additive manufacturing

Additive manufacturing (AM) refers to production processes that create **three-dimensional** (3D) parts using machines that successively layer material. AM, commonly referred to as **3D printing**, was originally created to help manufacturers quickly produce **prototypes** for traditional part production. Once created, manufacturers realized the technology could be used for an array of applications, such as producing industrial **tooling** and **end-use** products.

Traditional Manufacturing

Traditional manufacturing processes create end-use parts by **molding**, **forming**, or **cutting** a **workpiece**. Typical molding or forming applications include **injection molding** and **rolling**, while **subtractive manufacturing** includes **metal cutting** and **grinding**. Though these processes can create large volumes of parts, they have important limitations, particularly in **part complexity**.

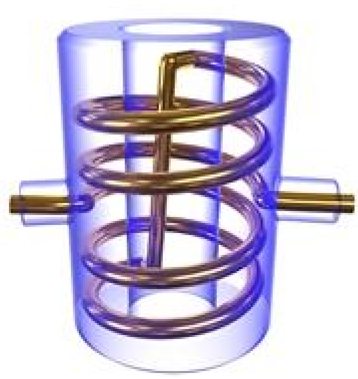


Additive Manufacturing

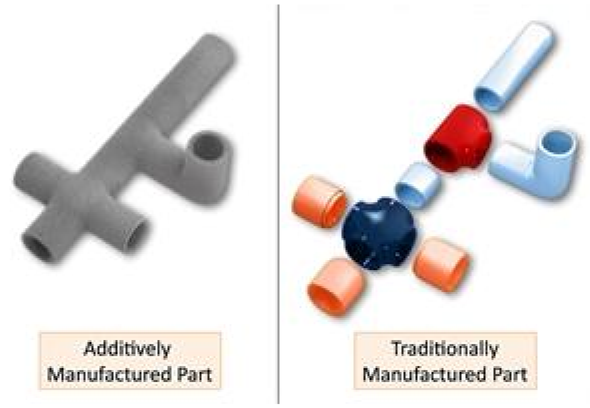
In addition to allowing for increased part complexity, AM can combine components that would otherwise have to be created separately, and AM allows for **mass customization**. AM requires specific equipment for actual part creation, but the design aspect of AM takes place through standard or AM-specific **computer-aided design** (CAD) programs.

There are a several advantages to using **AM**. From a manufacturing perspective, AM processes often help lower some aspects of **lead time**, reduce waste, lower the final weight of a part, and require minimal processing of **CAD** data. In addition, AM processes can increase production efficiency by leveraging design software. Although some industrial AM machines can have quite large build areas, most AM machines typically allow for a more adjustable use of space than traditional manufacturing since each AM machine can create an entire part on its own. A single machine, or a smaller number of machines, takes up less space and can be moved more easily.

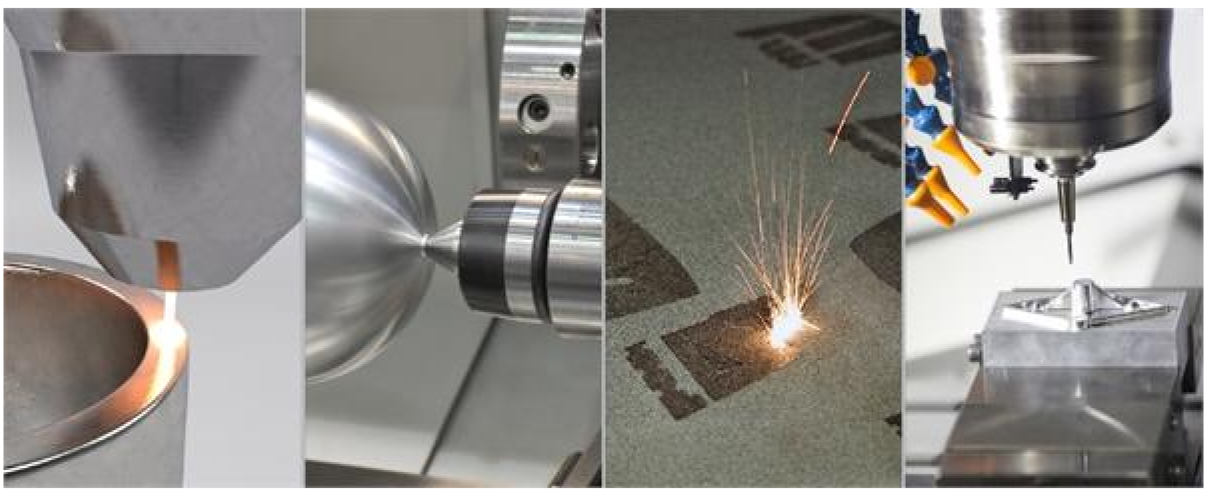
From a design perspective, AM offers incredible flexibility. AM parts can have more varied **features** than traditionally manufactured parts, including features that would be hard or impossible to create using other processes, such as intricate, curved **internal channels**. Similarly, some traditionally manufactured parts require so many unique features that **engineers** must create the part by combining several other smaller parts. Using AM, engineers can create those same parts in one piece, allowing them to focus on optimizing functionality. Other key design advantages of AM are the ability to easily modify and customize a design and, with some AM processes, adjust the material type and composition in various places in a part.



Part with Internal Channels



Part Integration



AM machines have slower build rates than traditional manufacturing machines.

Many disadvantages of AM relate to manufacturing considerations. Most AM processes currently have slower **production rates**, or **build rates**, than traditional manufacturing. AM equipment and materials are expensive, particularly since AM machines cannot offset their costs by producing the same part volume as **automated** subtractive manufacturing. Additionally, some AM processes may need extensive post-processing or require some kind of subtractive process in order to create a finished part.

From a design standpoint, the biggest constraint of mainstream AM technology is size. Common AM systems can only build objects that are one **cubic yard** or smaller in size. However, there are larger, more expensive machines capable of **big area additive manufacturing** (BAAM). For manufacturers switching to AM or integrating it into a traditional manufacturing process, training engineers to use AM requires a time investment, which itself may bring added costs. Successful AM design requires a thorough knowledge of the capabilities of a specific type of AM process, particularly the machine and materials it uses.

Though the general advantages and disadvantages are applicable to all AM processes, engineers should familiarize themselves with the specifics of the AM process they will use. The **American Society for Testing and Materials** (ASTM) groups AM techniques into 7 categories.

In **material extrusion** processes, such as **fused deposition modeling** (FDM), material is heated and drawn through a **nozzle** and then deposited on a **build platform** in successive layers to create a part. Material extrusion machines often have at least two nozzles, one for **build material** and one for **support material**. Material extrusion is most often used to make **thermoplastic** parts and is relatively inexpensive. Material extrusion is also slower than some other AM methods and finished parts often have poor **surface finish**.

Vat photopolymerization methods use a single-point **ultraviolet** (UV) **laser** to selectively **cure** layers of **liquid photopolymer**, or **resin**. The most common vat photopolymerization method is **stereolithography** (SLA) where the part is lowered into a **vat** after each new layer is created. Parts created through vat photopolymerization are extremely detailed and easily customizable but lack **strength**.

Powder bed fusion (PBF) methods use a heat source, such as a laser or **electron beam**, to selectively **fuse powdered** material in layers. Like SLA, PBF techniques involve lowering the part, held in a **powder bed**, after a layer is created. A roller or **scraper bar** then distributes more material over the part so that the next layer can be created. PBF can be used with a variety of materials. **Selective laser sintering** (SLS) uses a laser to create parts out of **plastic**, while **direct metal laser sintering** (DMLS) uses an electron beam or laser to create parts out of **metal**. SLS is a powder bed fusion method that uses plastic or ceramic materials. **Selective laser melting** (SLM) is like selective laser sintering (SLS) but produces stronger and denser parts by fully melting build materials. **Electron beam melting** (EBM) is a PBF process that takes place in a vacuum in order to melt metal powders at higher temperatures to improve mechanical and **physical properties**.

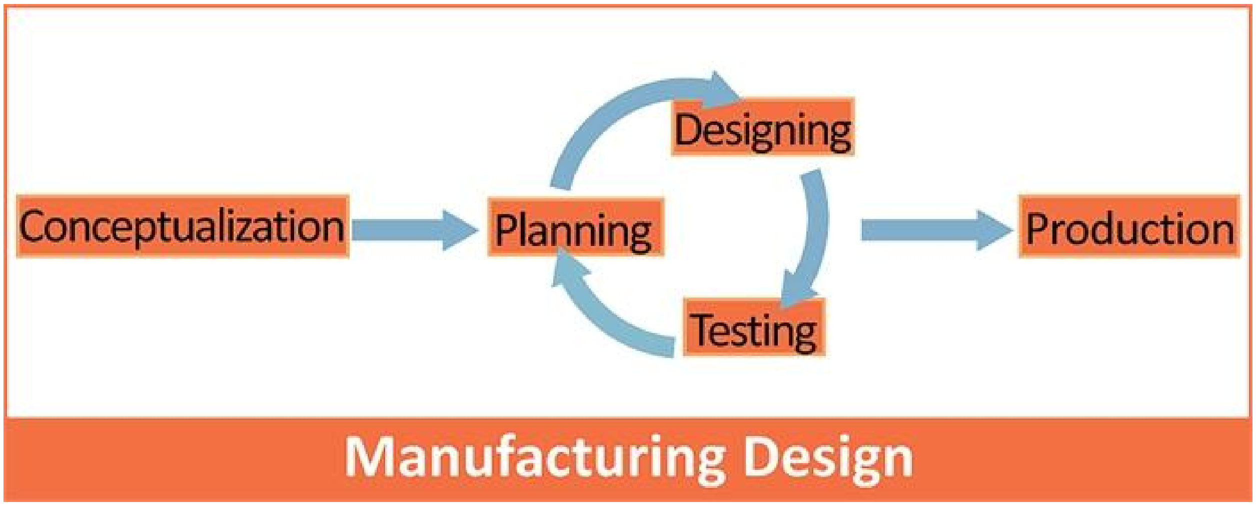
Material jetting systems work much like traditional **two-dimensional** (2D) inkjet printers to deposit liquid photopolymer onto a build platform, which is then instantly cured with a UV light to build a 3D part layer by layer. Material jetting is considered one of the most accurate of the AM methods. A typical printhead may contain hundreds of individually controlled drop-on-demand nozzles. This ability to control multiple nozzles gives designers the ability to **modulate**, or adjust, the types of material and color used to build a part, which makes it ideal for full color and multi-material parts. Though fast and precise, parts created using material jetting are made of UV sensitive material that degrades over time.

Directed energy deposition (DED) uses a laser beam to melt powered metal or metal wire and deposit it directly on the build platform in layers. DED allows for careful control of **grain structure** and material **gradation**, which means engineers can create end-use parts with purposefully designed material and physical properties that vary in different places in the part. However, DED has a limited range of build material, and DED parts often have poor surface finish.

Binder jetting, which deposits binder in a bed of powdered material to create the part, combines material jetting with PBF. Binder jetting machines use a print head to dispense a liquid bonding agent, like a glue, to selectively join raw material powder layer by layer in a powder bed to form a solid object. Binder jetting can build parts from powdered metals, ceramics, or sand but are often not stable enough to be used in any high-stress environment.

Sheet lamination describes a process in which a feedstock roll is fed onto the machine's build platform in separate sheets which are bonded together. Sheet lamination can use a variety of different materials and bonding methods to create parts. The materials are cut into the shape of the part with subtractive manufacturing methods. Sheet lamination is often considered a hybrid manufacturing process because it combines both additive and traditional manufacturing methods.

Design for any manufacturing process involves two major considerations: **functionality**, or the desired performance and application of a new part, and limitations of the manufacturing process. The basic manufacturing design process follows five steps: **conceptualization**, **planning**, **designing**, **testing**, and **production**.



Conceptualization refers to the initial visualization of a part. Planning, designing, and testing are the steps involved in physically building and assessing the proposed part, including creating **blueprints** and prototypes, to be mass manufactured in the production step. Usually the planning, designing, and testing steps require extensive revisiting as prototypes are created and studied for functionality, as well as to ensure the part can be created using the manufacturing processes available to the engineers. Because engineers must create and test several prototypes to reach a finished product, these three steps can require a great deal of time and money.

Design for traditional manufacturing is called design for manufacturability or **design for manufacturing** (DFM) and follows the five steps of a typical manufacturing design process. The traditional prototyping process often involves reconfiguring tooling and machines for each prototype. However, once DFM reaches the production phase of the design process, it becomes very efficient and cost- effective.

Basic **design for additive manufacturing** (DFAM) follows the same five-step process as **DFM**, but the limitations of the manufacturing process are greatly reduced. When designing for AM, engineers are free to focus on the functionality of a part, including optimizing part complexity, finding opportunities for customization, and streamlining assemblies. Size issues can be overcome while still maintaining improved complexity, either through **BAAM** or through creating one finished product by combining several AM parts. Planning, designing, and testing are also streamlined in DFAM since creating prototypes does not require any additional tooling.

There are still challenges that accompany DFAM. Most AM machines can only process one category of material. **DMLS**, for example, can only create parts out of metal, while **FDM** usually uses filaments or pellets of thermoplastic material. Since AM machines are expensive, engineers will likely design for just one type of AM process. There are also specific design aspects that are unique to DFAM and must be implemented correctly, such as using **support structures** and focusing on **topology**. However, the opportunities for unique part creation in DFAM are already revolutionizing several manufacturing processes.

Big area additive manufacturing (BAAM)

AM helps shorten the planning, designing, and testing phases of manufacturing design. Courtesy of Stratasys.

When initially developed, AM was used exclusively for **rapid prototyping**. Rapid prototyping refers to using AM operations to create prototypes for a part that will be mass produced through traditional manufacturing. This process combines the accelerated development times of **DFAM** with the optimal build rates of traditional manufacturing.

Rapid Prototype Versus Finished Part

In rapid prototyping, engineers use AM to create **functional prototypes**, which allow engineers to test the functionality of a part design, and **conceptual models**, which allow engineers to communicate their design ideas more easily and concretely. Functional prototypes are exact replicas of the proposed part, matching the detailed specifications and material composition of the part design, while conceptual models serve more as **visual aids**. As with other AM processes, either kind of prototype can be built without any additional assembly directly after. Though using AM only for rapid prototyping imposes the design limitations of traditional manufacturing, the ability to quickly create prototypes still drastically reduces lead time by shortening the planning, designing, and testing steps. Additionally, rapid prototyping reduces material costs and scrap since prototypes are created on AM machines, rather than through subtractive manufacturing or other traditional manufacturing methods Though the role of AM in various industries is expanding, AM processes are still widely used for rapid prototyping.

Manufacturers are increasingly using AM to create end-use, near-**net-shape** parts for direct use by consumers. Though the limitations of AM will likely keep it from replacing traditional manufacturing, there are several applications for which AM is particularly suited.

The aerospace and automotive industries use AM to consolidate parts or to create parts with complex internal features or geometrical designs that could not be manufactured using traditional methods. In addition to improved part design, AM allows manufacturers to create lighter parts using lighter construction materials and streamlining the design. With AM, manufacturers can build parts with better functionality that take up less space. Common parts made with AM for these industries include **turbine blades**, **fuel systems**, and **drive shafts**.

The biomedical industries, particularly the dental industry, use AM primarily to mass-customize parts for a range of specific end-users. Customizing **implants** or **dental braces** can improve the function of those devices as well as increase user comfort. Additionally, many medical laboratories or research facilities require specifically customized equipment, such as **centrifuges**.

Creative and consumer-driven industries, such as jewelry and footwear manufacturing, have also found many uses for AM. Particularly, the design freedom of AM allows for the creation of unique, intricate, and complex products that would be hard to replicate using any other process. Additionally, AM is used to embed sensors in products and parts, to collect usage data for optimizing maintenance and continuous improvement.

In addition to rapid prototyping and creating near-net-shape parts, there are many other applications of AM processes.

AM can be used to create a wide variety of tooling for traditional manufacturing operations, which is sometimes referred to as using AM as a **secondary process**. AM tooling includes fixturing components, such as **jigs** created through material extrusion. These fixturing components help hold parts for assembly and **molds**, sometimes created through binder jetting, for a wide array of molding operations such as **sand casting** or injection molding.

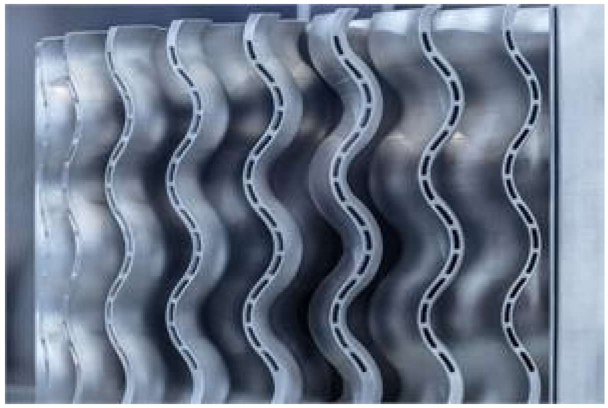
AM can also add features to a traditionally manufactured part. **DED** AM operations, for example, can create small metal features on a workpiece that has been shaped through metal cutting. Additionally, DED can be used to add **cladding**, or a layer of protective material, to a traditionally manufactured workpiece. DED can also be used to repair damaged parts.

A small AM part may also be added to a traditionally manufactured assembly, such as building an AM **gripper** for a **robotic arm** created through a metal cutting or metal forming operation. These combinations take advantage of AM's ability to create intricate features and traditional manufacturing's ability to rapidly shape large, simple workpieces.

Additionally, AM can be used to produce visual aids, such as building or architectural models for the construction industry, or presentation models for educational lectures, such as bone structures for the medical field.

Part complexity is one of the greatest advantages of AM. Creating additional part features, such as added channels for air flow in a **duct**, can be accomplished effectively with AM processes. Since parts are built layer by layer rather than through the use of rigid tools, there are few limits to the possible geometric complexity of any features. Curved features can transition seamlessly into sharp lines whenever it serves functionality. Additionally, AM can create intricate **lattice structures** that can increase the strength of a part while reducing weight. AM also allows for **hierarchical complexity**, which means the ability to design any shape across multiple scales.

Another key consideration related to part complexity is AM's ability to vary part thickness. A part's internal patterns can be made either **dense** or **porous** to facilitate or prevent the transfer of heat or energy. Some AM processes can modulate the types of material used to build a part through material **gradation**. For example, a **hand drill** is made of various types of plastic as it requires different levels of material strength at varying places on the tool. The handle, for instance, needs to be able to withstand the force of an operator pressing into it, while the bottom of the drill just needs to hold the **battery**. A material jetting process can build the entire drill, with varying types of plastic and without requiring further assembly, in a single operation. Manufacturers also use this process to layer different material types, a soft plastic on top of a rigid one for example, in parts where the properties of both materials are required. Some advanced DED processes can vary the microstructure of a metal part along with varying types of metal, resulting in extremely precise material gradation.

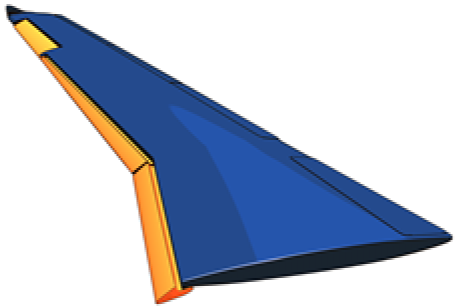


Complex AM Parts

AM Hand Drill with Material Gradation, courtesy of Stratasys

Functional complexity refers to the degree to which a manufactured part can perform a task, usually related to movement, immediately after being created. Most traditionally manufactured parts have limited functional complexity and must be joined with another part to be able to perform a task. For example, a traditionally manufactured **gear** will be able to spin on an axis immediately after production. However, to perform an actual function, such as forming a **gear train** on a **belt drive**, the gear must be mounted with other gears in a series. AM processes can potentially create an entire working gear train in one process, optimizing functionality and reducing the need for further assembly. Other functional components that can be built into an AM part include **joints**, **springs**, and **roller chains**. Additionally, manufacturers are increasingly using AM processes, such as material jetting, to embed **electronic** components directly into parts.

AM processes are also ideally suited for manufacturing "**smart structures**," which are components designed to perform differently depending on environmental factors. For example, a "smart" airplane wing would be able to adjust its shape depending on wind conditions to maximize performance. Smart structures are made from a range of seamlessly integrated parts and carefully designed material gradation. Many AM processes are well-suited to accommodating these design requirements.



Sensors embedded in airplane wings.

A roller chain created with AM.

Part integration builds on the concepts of part and functional complexity. DFM often involves making several smaller parts to create one finished product. The process of assembling smaller parts into one larger part takes additional time and sometimes additional tooling. AM processes do not limit part complexity and can create parts with incorporated functionality. This leaves engineers free to combine as many features, parts, and components in a single end-use part as possible.

Conventional Ductwork versus AM Ductwork

For example, conventional **ductwork** is created by connecting a series of discrete metal or plastic sections using **mechanical fasteners**. Assembly is time-consuming, and the large number of connections leave space for air to escape, reducing ductwork functionality. Though ductwork is generally too large for manufacturers to produce in one piece, AM allows them to build larger sections as a single unified part, reducing the number of connections and assembly time. AM engineers can also design the remaining connections on ductwork to fit with far greater accuracy. DFAM's ability to integrate parts frees engineers to consider a part as a single unit rather than discrete parts, improving the overall design and function of the end-use part.

Mass customization refers to setting up an AM process to create a large volume of user-specific parts. Mass customization is particularly useful with medical devices, such as implants, or assistive devices, such as dental braces or components of **hearing aids**. Unlike the other DFAM operations where an engineer is responsible for creating a part design for direct AM, mass customization requires a more flexible setup. In some cases, such as creating specialized tooling for a manufacturer, an engineer may design a basic version of the part and be prepared to adjust the design, material composition, or gradation based on the specific requirements of the customer.

Other end-use medical devices must match the unique specifications of a single consumer exactly. In these situations, it would be impossible for an engineer to design a unique part for each patient. Instead, engineers design unique **software** along with a compatible **modeling** or **scanning** technique that allows medical or other professionals to send a model, such as a dental or ear impression, or a scan to the AM facility. There, engineers can review the model or scan, adjust the design, and manufacture the implant or medical device. Though this kind of customization is particularly valuable in medical fields, it has a range of potential consumer applications, such as clothing or recreational gear manufacturing.

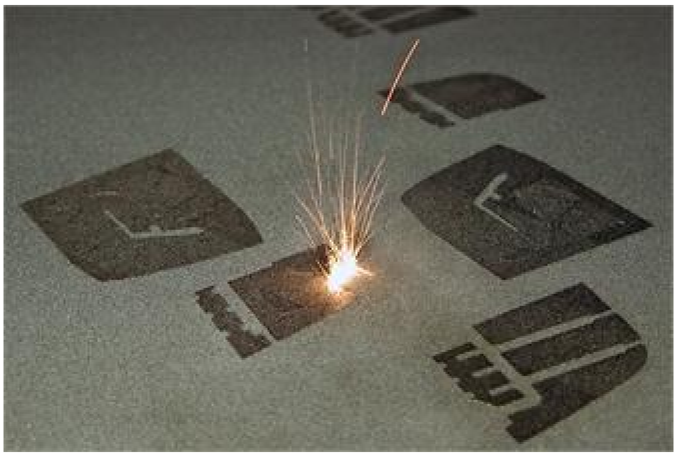
AM engineers can quickly adjust and customize a hearing device to a customer's specifications.

Dental impressions allow AM engineers to create customized dental braces.

When selecting an AM process, engineers consider the desired material composition and characteristics of the part and the advantages and disadvantages of various AM operations.

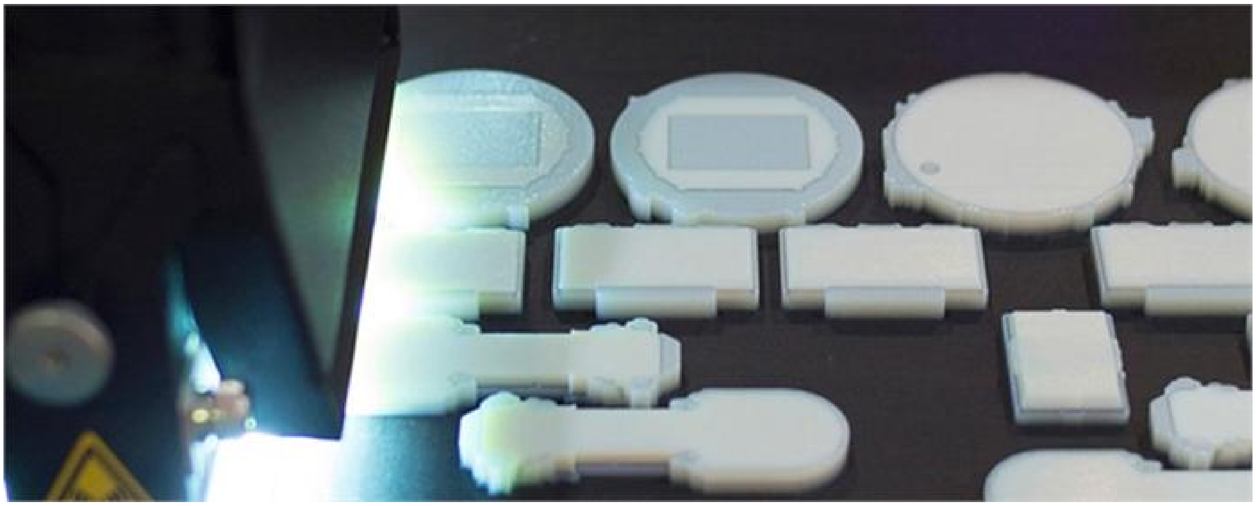
Plastic Filaments for FDM

The material composition of the part determines which AM process engineers can use to make a part. Making a metal AM part requires engineers to use one of the metal AM processes, including DMLS, DED, or binder jetting, which have varying mechanisms for turning powdered metal into a solid, finished part. Various plastic parts can be made through **SLA**, **SLS**, material jetting, or FDM, as well as binder jetting. **Glass** or **ceramic** have specific AM processes with which they work best. For example, glass parts can be built using material extrusion, and ceramic parts can be built using powder bed fusion, vat photopolymerization, or advanced sheet lamination methods. Within each category of material, such as plastic, there is an incredible range of types of material to choose from with vastly different mechanical and physical properties.



DMLS

Once engineers identify possible AM processes, they must consider the advantages and disadvantages of each option. DMLS, for example, can create strong metal parts at a relatively low cost but they often require extensive **post-processing**. Binder jetting is generally faster than other AM metal processes but finished parts can lack strength. For plastic parts, material jetting creates highly accurate, detailed parts, but they often suffer from structural weakness. FDM is an accessible, low-cost process, but parts have poor surface finish and limited end-use application.



Mixed Tray Build for Material Jetting, courtesy of Stratasys

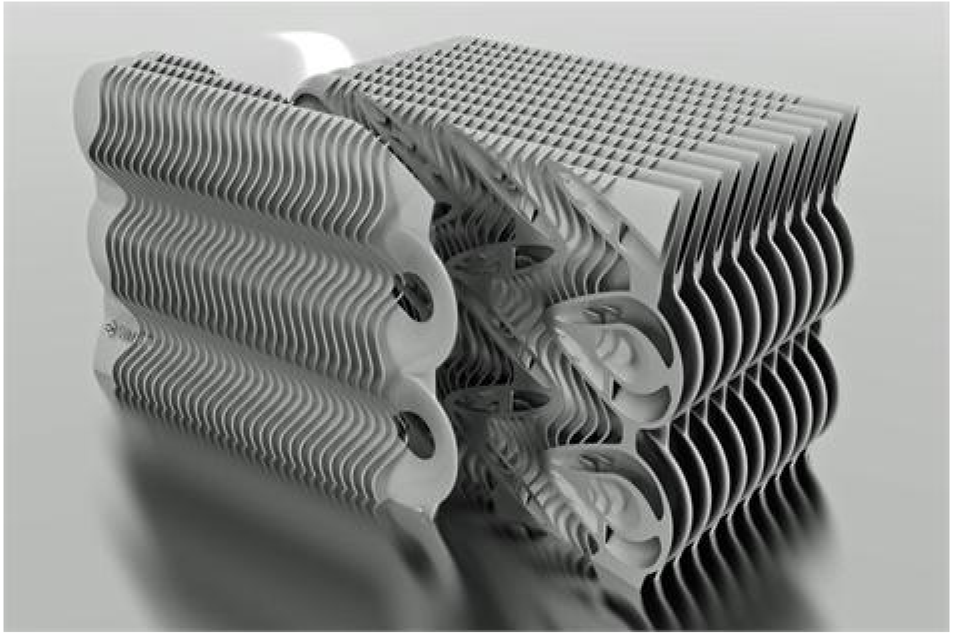
Each AM category of AM has unique, adjustable variables, or build parameters, that control an aspect of the building process. Basic considerations for most AM processes involve ensuring the correct materials are installed in the machine and that the layer thickness is set correctly. For example, in FDM thicker layers are deposited faster, while thinner layers lead to more accurate parts with better surface finish. For PBF machines, build parameters can include things like bed temperature, electron or laser beam intensity, and layer thickness. Other machines, such as material jetting machines or more advanced FDM machines, can process a number of materials in a single print run and have a variety of possible layer thicknesses.

Other **build parameters**, such as material **deposition rate**, may be adjustable on a particular machine. For some advanced AM processes, creating material gradation in a part may require setting varying levels of heat at which to expose a material to alter its microstructure. These variables are often controlled by building software rather than by manual adjustments.

CAD

The most used AM design tool is CAD software. CAD is a **solid modeling** program that allows engineers to create a 3D computer representation of the part they'd like to manufacture. CAD software allows engineers to create all possible 3D shapes, from spheres to cylinders to cones, and manipulate them to generate intricately shaped features. Engineers can draw parts in CAD but having a blueprint with specified dimensions simplifies the process. Other CAD features include the ability to select the desired **resolution**, related to surface finish, and indicate where different materials should be used to build different part features. With traditional CAD, the ability to use different build materials is typically limited to distinct part features, such as a handle. However, newer generations of CAD can link to other modeling software to create more design possibilities.

Engineers using CAD must also understand the shape limitations of the particular AM process for which they are designing. These limitations vary, but general considerations include minimum **wall thickness** and minimum **hole diameter**.



Design tools can enable complicated internal structures.

Traditional CAD programs offer a range of benefits, in particular allowing engineers to interact with a model that mimics the shape of the desired finished part. However, CAD is not well suited for modeling parts with material gradation or high levels of geometric and hierarchical complexity. Because of the limitations of CAD, engineers are developing other types of modeling software that are better suited for designing AM parts.

Some developing software focuses on **implicit modeling**, which involves creating a continuous representation of a part from the interior to exterior. Although implicit models do not convey precise edges or boundaries, as in CAD models, they do allow engineers to define material gradation more precisely. Other modeling software would potentially allow engineers to also design, when applicable, microstructure and **thermal input** models, allowing for even more precise control of material composition and gradation. Ideally, AM design software would take advantage of a range of modeling types to optimize part design.

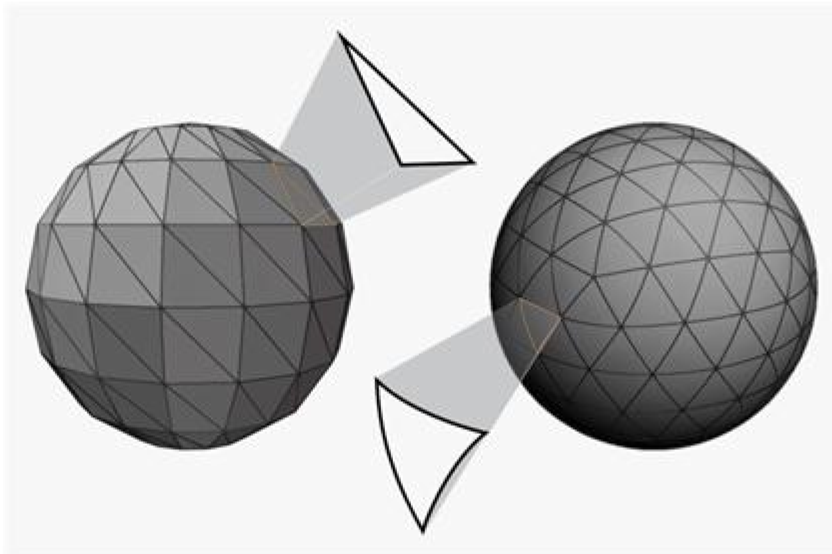
In some cases, engineers reverse engineer an already made part to improve it using AM processes. **Reverse engineering** involves scanning a physical part to create a 3D CAD model. Common scanning techniques are **laser scanning** and **touch-probe technology**. Both processes require that the part be held, preventing engineers from scanning the entire part and leaving gaps in the scan. More advanced scanning techniques, such as **computer tomography**, can scan the entire part as well as internal features.

The information collected in the scan is called a **point cloud**, which is a series of unconnected points that represent an object's shape. Engineers use specialized software to connect the points and create the model. These models may still have small gaps that an engineer must correct.

Once a part has a 3D model, engineers can quickly make changes to optimize a design or add features and manufacture the new part through an AM process. Reverse engineering can also be used to customize a part that was originally created through traditional manufacturing. Additionally, reverse engineering can be useful if it becomes more cost effective to build a traditionally manufactured through AM, such as if new specifications require a part with material gradation.

Laser Scanning

Point Cloud



STL Files Versus AMF Files

Once the model is completed, engineers must convert CAD files to a file type compatible with the AM machine. The most common AM output file type is an **STL** software file. STL files represent the 3D approximation of a part in a series of interconnected triangles, allowing the model to be sliced into layers. The layers are then recreated by the AM machine. Engineers usually need to examine the STL file for errors and fix them before building the part. Breaking the model into more triangles leads to higher resolution, which creates parts with better tolerance and surface finish but takes longer to build. STL also carries over CAD's limited ability to build different sections of a part of different material. Though STL is still the most common AM output file type, newer, more sophisticated output file types like **additive manufacturing files** (AMF) are allowing for improved surface finish, **tolerance**, and material gradation. For example, AMF files can also use curved triangles, which enables the designer to create more complex shapes compared to the flat triangles of the STL format.

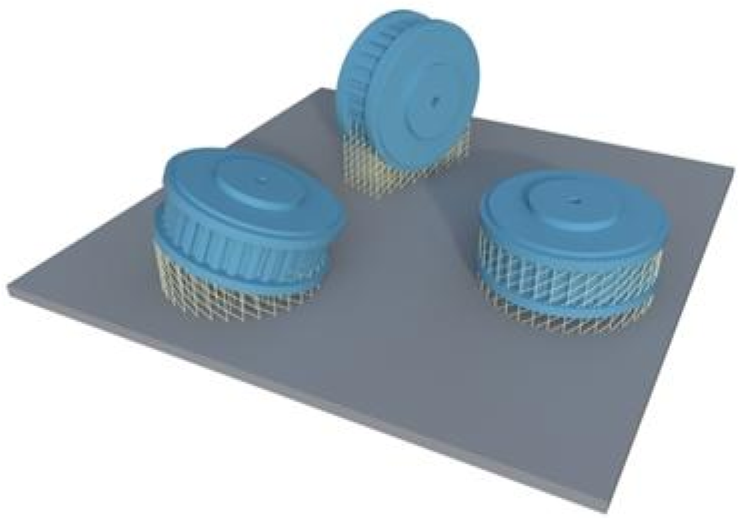
Once an STL file is loaded into a machine, engineers place support structures and select part orientation. **Support structures** are removable structural components, similar to **scaffolding**, that hold an AM part during manufacturing. AM parts are built through stacking very thin layers of material. The initial layers are often unable to support their own weight.

Support structures are made of the same material as the part or of a different, more easily removed material. Once the part is built, support structures are removed using **mechanical** or **chemical** means. Mechanical means involve physically separating the support material either by hand or with a tool. For polymer parts, chemical means are used to remove support structures made of a different material than the part with a **chemical bath**.

The number of support structures a part requires depends on part shape, with more complex shapes requiring more support. Support structure specifications also depend on part orientation. Optimizing part orientation includes considering the support structures needed to manufacture a part in a particular position. Limiting support structures is important, as removing them will cause minor surface defects. Some parts, such as one with a solid, uniform shape, may not require support structures. Similarly, some AM processes may not require support structures. In DMLS, for example, the powder bed provides some part support.

Part with Support Structures

Chemical baths can be used to remove support structures.



Part orientation determines the placement and number of support structures, which affects part quality.

Part orientation refers to how the part will be positioned in the AM machine while it is being built. Part orientation affects part quality, as some parts will have better accuracy and tolerance if built at a particular orientation. A cylinder, for example, will be more accurate if it is built vertically, set like a column, rather than horizontally. On complex parts, features that require tighter tolerances should be positioned in a way that limits support structures. AM part orientation is very flexible. Sometimes unique orientations, such as setting the part at a 45° angle, may reduce the need for support structures, particularly on crucial part features, such as moving features.

Part orientation also affects build rates. AM processes have slow build rates, but those rates can be improved by maximizing part orientation so that as many parts can be built in a single operation as possible. Generally, vertically oriented, or taller, parts take more time to build because of the number of layers that must be deposited, though they sometimes require fewer support structures. Additionally, a part's mechanical properties can vary based on part orientation as it affects how material will be layered to build the part.

Most AM parts require some form of **post-processing**. Post-processing is any procedure used to finish a part after it has been built. Necessary post-processing will depend on the AM method and material, but some common post-processing includes support structure removal, **abrasive finishing** to improve surface finish, the application of specialized **coatings** to improve functionality, and **heat treatment** to improve mechanical and physical properties. Some post-processing procedures are only used on certain types of material. For example, heat treatment generally should not be used with plastic parts. Aesthetic improvements like painting or **plating** are also considered post-processing.

Each AM operation requires varying degrees of post-processing. Plastic FDM parts often only need abrasive finishing and **sealing**, which can be done quickly. Metal parts created through PBF usually require more extensive post-processing, including some form of heat treatment, such as **curing** in an oven, in addition to abrasive finishing or coating.

The use of an AM part also determines the necessary post-processing. An FDM part used as a visual aid may just need abrasive finishing, while a metal jet engine part will require heat treatment, abrasive finishing, coating, and potentially more so that it can perform safely in a high-stress environment. Though post-processing is usually not a consideration during initial design phases, engineers will likely need to determine the necessary post-processing to ensure a part meets operating, consumer, and any other specifications.

Coating Parts

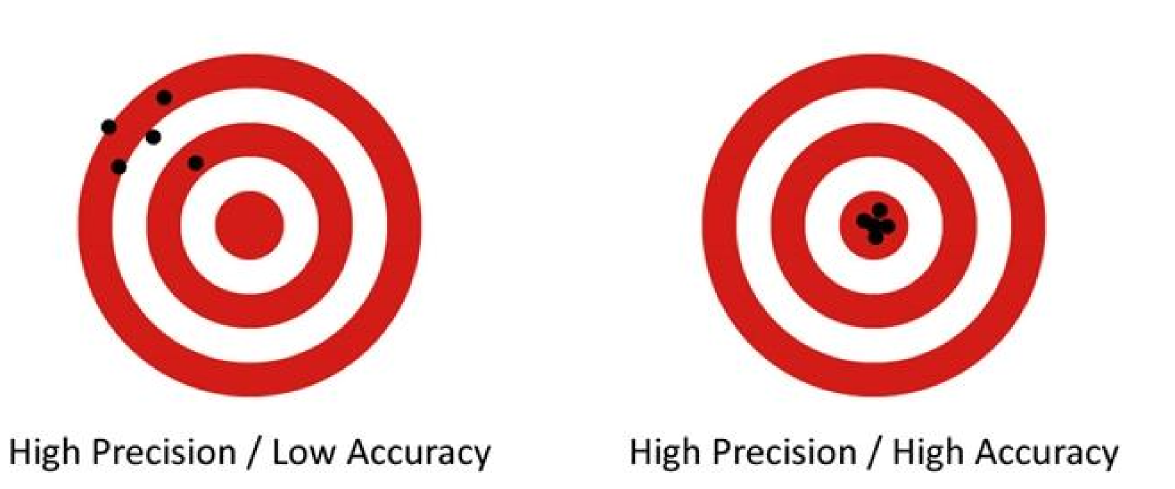
Abrasive Finishing

202: Metrology for Additive manufacturing

Metrology is a term used to describe the science of **measurement**. In a manufacturing setting, obtaining measurements involves **inspection**, which is the process of examining a part either during or after its creation to determine if it conforms to **specifications**. Inspection enables manufacturers to maintain consistent part specifications and standardization, which ensures that parts of the same size are interchangeable. Inspection also uses metrology as one way of ensuring **quality**.

A growing number of manufacturers are using some form of **additive manufacturing** (AM), which refers to a variety of different processes used to make complex **three-dimensional** (3D) parts. Metrology uses different contact and noncontact methods to measure a part and determine if the part's **dimensions** are within proper **tolerance** or if any **defects** have occurred. Since additive manufacturing can create part structures that are incredibly complex, traditional forms of metrology may not be able to measure the complex internal structures of an AM part, which can pose inspection challenges. In addition, manufacturers may use an AM technique as a **secondary method** to assist **traditional manufacturing** methods like **casting** or **molding**. Whatever the AM process or application, metrology can ensure that AM parts meet the same standards and provide the same reliability of any traditionally manufactured part.

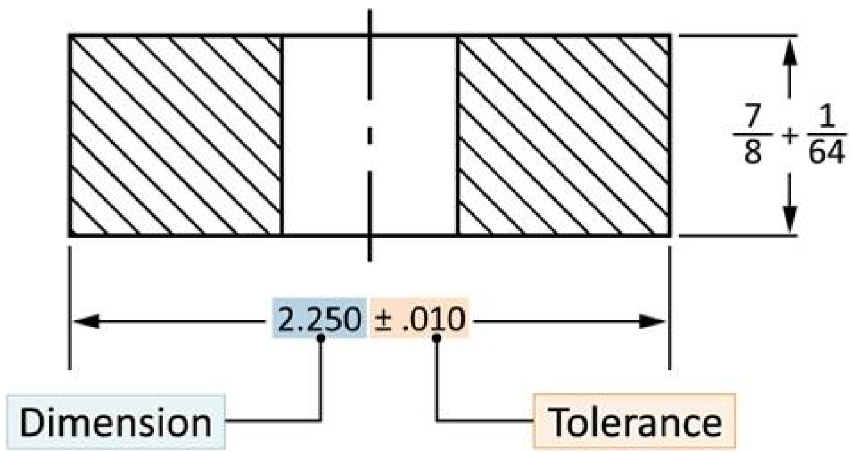
Metrology uses the concepts of **accuracy** and **precision** to determine if a part's measurements meet specifications. A dartboard example can show the difference between the two basic concepts.



Accuracy demonstrates the exactness of a measurement compared to the desired result. For example, the closer darts land to the bullseye, the more accurate they are. Precision, however, demonstrates how similar multiple measurements are to one another, regardless of their accuracy. Precision, also referred to as **repeatability**, tracks measurements across multiple parts or machines. If they are precise, measurements will show the same or very similar results under unchanged conditions. For example, if the darts land very close to one another on the dartboard, they show high precision. If they land far apart from one another, they have low precision.

Ideally, a measurement should be both precise and accurate. If the darts are clustered tightly together on the dartboard but miss the bullseye, then they demonstrate high precision and low accuracy. In order to have high precision and high accuracy, the darts must all hit the bullseye in the same place. Similarly, to have high precision and high accuracy in metrology, parts should be within tolerance consistently over multiple measurements.

A part's measurements are also known as its dimensions. Every part print or specification includes the part's ideal dimensions. However, parts are practically never the same exact size or shape as their intended dimensions because of **variation**.



In metrolology, a tolerance indicates the acceptable amount of **deviation**, or error, a part can have while still meeting the requirements for its intended functions. Reducing variation improves part quality but generally increases the time, effort, and cost to make a part. Some parts may not require high precision and accuracy to function properly, so the time and cost that reducing variation involves are unnecessary. A **tolerance range** creates a balance between improving precision and accuracy and reducing time and costs by determining an acceptable amount of variation from the ideal dimension.

For parts that require higher accuracy, measuring instruments may require **calibration** to ensure a part is within the correct tolerance range. For example, some tolerance ranges may only be as wide as the width of a hair. If an instrument is even slightly off, it may lead to defects and bad parts. Inaccurate instruments can also lead to good parts being rejected during inspection.

Different dimensional measuring tools can determine whether a part is within tolerance. Although there are many ways to classify measuring equipment, dimensional measuring instruments can be divided into six general categories: hand devices, contact **coordinate measuring machines** (CMMs), noncontact CMMs, **optical comparators**, and **air gages**.

Common hand devices for measuring part dimensions include **gaging instruments**, which determine whether or not a part is within the acceptable tolerance range. Essentially, a gage either fits or does not fit within or around a given part **feature**. Other common types of hand measuring devices like **calipers** and **micrometers** utilize **variable inspection** techniques, which means that they move and adjust to measure various part dimensions. Calipers include a pair of movable jaws on one end and a long beam containing a marked scale that functions like a precision slide ruler on the opposite end. Placing the jaws in or around a part feature causes the scale to move to indicate its measurement. Micrometers are U-shaped measuring instruments with a threaded spindle that slowly advances toward a small **anvil**, similar to a caliper's jaws. Typically, micrometers have greater accuracy than other hand devices. However, some **AM** parts, like those made from human tissue or other **biomaterials**, may prove too fragile for these inspection instruments.

For parts too large or complex to measure with hand tools, inspectors may use a contact CMM, which uses a probe with a **stylus** that makes physical contact with multiple points on a part. Contact CMMs record one single point each time they touch a part's surface. Metrology software interprets the data about each point's location to determine if a part is within tolerance or not. The most common of these machines, a **bridge-type CMM**, has two vertical supports and a horizontal beam holding the probe. Other contact CMMs, like a **gantry-type CMM**, can measure objects as large as a car. Like hand devices, contact CMMs may damage fragile and delicate parts.

For more fragile or delicate parts, an inspector may use a noncontact CMM, which uses light and sensors rather than a probe to determine a part's dimensions. For example, **3D scanners** can use a **laser** to create a large collection of data points called a **point cloud**. Each point in the point cloud represents a physical location on the part, which an inspector can use to build a **3D computer-aided design** (CAD) model. Each point in the point cloud represents a physical location on the part.

Optical comparators, or **optical projectors**, are instruments that project a **two-dimensional** (2D) image of a part onto a screen to compare the shape, size, and location of its features to the original. Typical optical comparators work well for measuring **profile** features of a part, but not for depth or internal features.

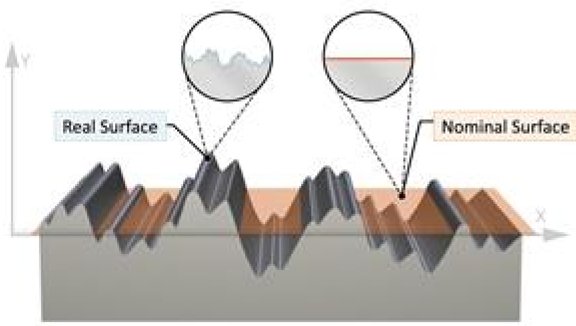
To inspect the **internal diameter** (ID) of a high volume of parts with tight tolerances, an inspector might use an air gage. Air gages are inexpensive, precise noncontact **pneumatic** instruments that use pressurized air to probe a part. For example, an air gage can measure the ID of a metal part by filling the part opening with air. This can accurately and quickly determine part deviations within 0.0001 of an inch (0.025 mm).

The surface texture of every AM part varies depending on the part's function. For example, the outside texture of a bearing requires a smooth surface, while a wrench handle may require a rough surface for gripping. Metrology is used to measure the different degrees of variation or deviation between the actual surface of the part, referred to as the **real surface**, and the part's specification, referred to as the **nominal surface**. In metrology, the term **measured surface** describes the difference between the nominal surface and real surface.

Surface finish inspection can reveal deviations like **flaws**, **roughness**, and **waviness** on the real surface of the part. In order to inspect surface finish, inspectors may compare the surface of an AM part to a standard sample, such as a **surface replica block**, using sight and touch. Inspectors can also use noncontact measurements with a device like an optical comparator to make comparison measurements. If a part requires a refined surface finish, an inspector may use a stylus-type device, like a

profilometer or **surfometer**, to make direct measurements. Similar to a **CMM**, the stylus probes the surface irregularities and converts them into an electronic signal.

Since AM processes create parts in thin layers, small ridges will remain on the finished part surface. For example, **binder jetting** has a lower surface quality compared to other AM processes. The surfaces of these parts are often porous, like a dried sponge and will typically require some type of **post-processing** like **infiltration** or painting.



Measured Surface

Profilometer

This machine performs destructive hardness testing.

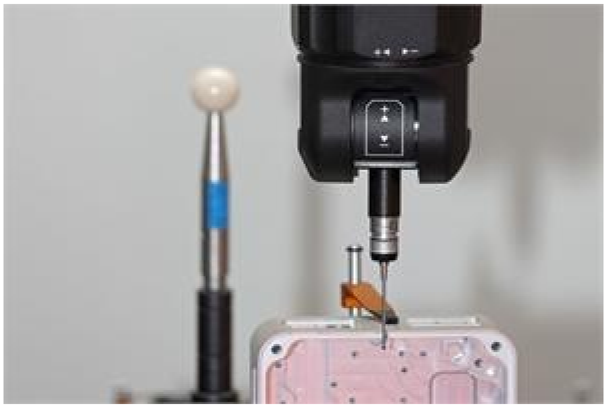
The increasing use of AM for end-use parts has increased the need for inspection internal features and part structures. Since AM methods fuse raw materials, it is essential to confirm that a part has fused and solidified correctly and has maintained the properties necessary to function. Metrology can use both destructive and nondestructive testing methods to analyze **porosity**, internal dimensions, and **wall thickness**. **Destructive testing** includes taking a random sample from a production line and inspecting it in a way that breaks or damages the part, which turns it into scrap. For example, an inspector can confirm that a part run's internal structure meets specifications by cutting a sample part open and inspecting it.

This machine inspects parts using X-rays.

Nondestructive testing (NDT) includes inspection processes that evaluate a part's properties and performance using methods that do not damage the part. A common method of nondestructive testing is **x-ray computed tomography** (x-ray CT), also known as microCT, which creates a 3D representation of a part's interior to show very fine internal details. For example, inspectors can use X-ray CT to measure internal porosity, or the small spaces or voids within a solid part. Other common NDT methods include **eddy current testing** (ECT), which sends electrical currents through metal parts to detect flaws, and **ultrasonic testing** (UT), which uses sound waves to detect part issues.

A CMM gathers measurement data through a **contact probe**, which has a stem-like shaft with a stylus that touches a part. The stylus typically has a synthetic **ruby** tip that acts as a precision tip to record measurements. In AM, CMMs can use contact probes to inspect print-on-demand parts or qualify specialized tooling. For example, contact probes can reduce the risk of production **downtime** by inspecting 3D-printed **jigs** or **fixtures** before they are used on the production floor.

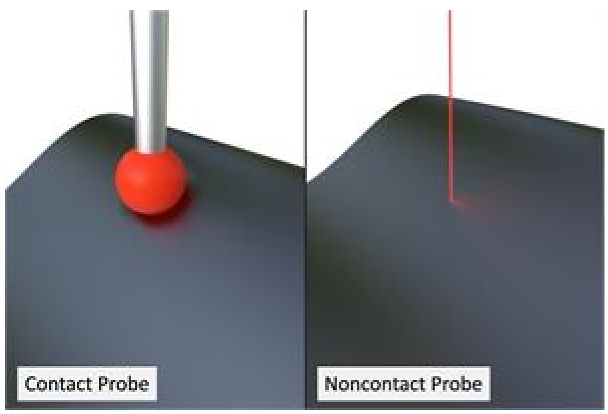
One common CMM contact probe is the **touch trigger probe**, which measures parts by generating an electronic signal every time the stylus touches an inspection point. It contacts multiple points and uses software to fill in the gaps between points to measure the full part dimensions. Although touch trigger probes are slow, their accuracy makes them ideal for AM parts with complex geometry. For faster contact probing, engineers may use a probing method called **continuous analog scanning** (CAS). CAS probing can deliver a continuous stream of measurements, which makes it ideal for curved surfaces.

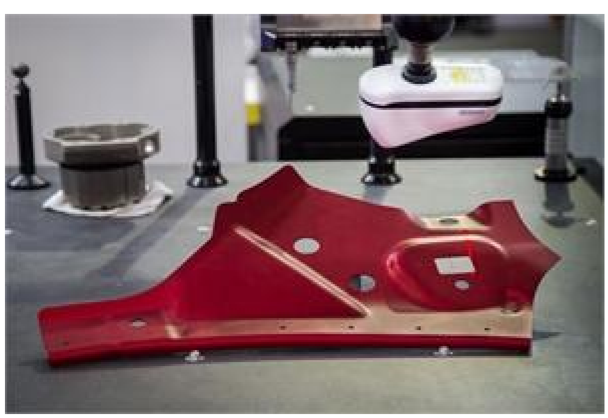


When a part is not suitable for contact probing, an inspector may choose a CMM **noncontact probe**. For example, an AM part may have delicate features that will break or deform if touched by a stylus. In other cases, a part may have a flexible surface that bends or distorts under the pressure of a contact probe, which will result in an inaccurate measurement.

Common noncontact probes include **laser probes**, which use a focused beam of light to probe the surface in a similar way to the stylus on a touch trigger probe. However, instead of touching the part surface, a lens on the probe reads the length of the laser beam in order to take measurements. Unlike contact probes that touch only certain points on a part, a laser probe can measure the entire surface of a part, which increases accuracy and precision. For example, a laser probe can scan the entire part and use software to create a **CAD** file that an inspector can compare to the original part specifications.

Another type of noncontact probe is a vision probe, or video probe, which creates a digital image of a part and turns it into **pixels**. Pixels are the smallest pieces of a digital image. The pixels act as data points in a point cloud, which software can measure against the original CAD design. Although not as accurate as a laser probe, engineers may use vision probes for inspecting smaller or two-dimensional (2D) parts. Although not as accurate as a laser probe, engineers may use vision probes may be used for inspecting smaller or **2D** parts.





Laser scanning probe

Although metrology devices can collect large amounts of measurement data, the unique characteristics of AM parts can create challenges for inspection.

Standards agencies like the **International Organization for Standardization** (ISO) have developed standards for some AM processes, like **powder bed fusion** (PBF) and **directed energy deposition** (DED),that compete with standards for traditional manufacturing processes. However, many AM processes lack industry-wide standards for part qualification, which forces companies to define their own standards of success. For example, the dimension and tolerance specifications for AM structures like **lattices** might vary across different companies, which can lead to substandard parts.

Since using AM for end-use parts is relatively new, metrology standards do not exist for many AM parts, which may cause an engineer to overlook problems early in the build. For example, a manufacturer may use AM technologies to build a fuel pump for a helicopter. Typically, an inspector uses a metrological device at the end of the build to verify that the finished part for the helicopter meets design specifications. However, during the build process, a deviation may occur early in one of the thin build layers, which might irreversibly affect the final build. A manufacturer may waste time and material building a defective part that they will have to scrap immediately.

In order to compensate for unique process variations, many AM parts for end-use applications need more rigorous inspection than traditionally manufactured parts. This can increase production time and time-to-market for end-use parts. For example, some binder jetting parts may need an additional infiltration process to strengthen them, which may require an additional round of inspection.

Many AM parts have a high degree of surface roughness, which can make contact probes very difficult to use. For example, **fused deposition modeling** (FDM) produces some of the roughest surfaces of all AM processes because of the way it builds parts in layers.

Environmental factors can affect measurement accuracy. For example, variations in temperature can impact a CMM's ability to collect accurate data from an AM part. To compensate, inspectors may measure a part with tight tolerances in an environmentally controlled laboratory. In addition, inspectors may use a device that records the temperature on both the CMM and the AM part.

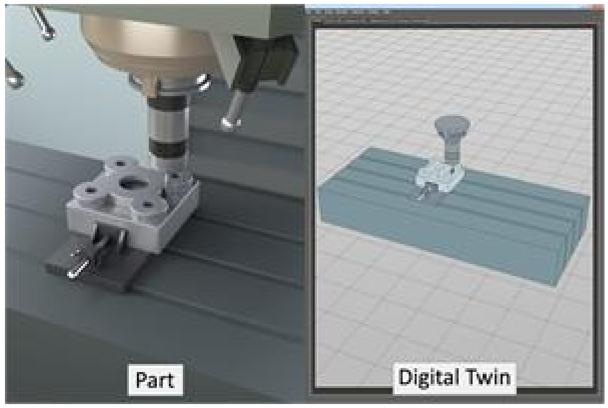
After printing, most AM parts will need post-processing or **finishing**, which refers to is a group of procedures used to clean parts, improve tolerances, or create an attractive surface finish on parts. Post-processing includes removing any external **support material** used in the build, which requires specific techniques to avoid damaging any delicate part features. Often, completed AM parts are subjected to thermal treatments like **curing** or **sintering** to further solidify and strengthen them. In many cases, post-processing for AM parts can take several days, which can significantly extend inspection time. Instead of waiting until a part is complete, manufacturers may consider inspecting it at each stage of production. The increased opportunities to inspect an AM part can reduce scrap and increase the overall speed of production.

Part of a post-processing inspection routine should include unused material retrieval from the machine. Many AM processes can recycle unused powder or plastic. For example, a manufacturer may use uncured liquid resin in a **vat photopolymerization** tank for several weeks at a time. However, mixing unused material with used material can affect future builds and measurements. Reused material should be stored in separate containers to help avoid future part defects.

The **Industrial Internet of Things** (IIoT) is a network of **smart** industrial technology, which is made possible by sensors in physical objects. The IIoT includes digitally connected tools and other machines that produce data, including metrological systems. Many common inspection tools and devices have a digital component, but newer innovations such as the **digital twin** and **digital thread** require inspectors to work in a more collaborative environment. For example, measuring equipment such as 3D scanners traditionally only communicated in one direction to send measurement results. Now, many 3D scanner systems can send information like part specifications from the design engineer. Being able to send and receive data makes it possible to provide **real-time** feedback and analysis.

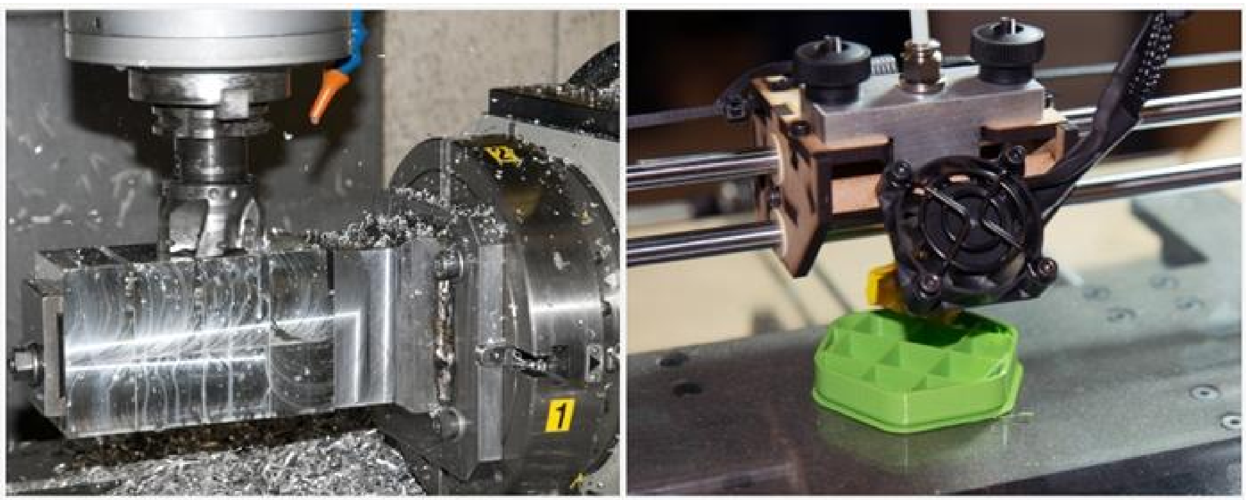
Smart technology relies heavily on metrological systems to ensure a part is made consistently within design specifications and tolerance. For example, inspectors can use 3D scanners to create a complete 3D digital image of a part, which can then be used to create a digital twin. A digital twin is a fully detailed representation of a part or machine. However, in order for a digital twin to be complete, it must include metrological data on dimensions, surface texture, and internal structures to ensure the part remains within tolerance throughout the manufacturing process.

Scanner sending information.



Digital twins represent physical parts.

211: Additive Manufacturing Materials Science



Unlike traditional manufacturing, additive manufacturing layers material to create a part.

Additive manufacturing (AM) is a versatile field that encompasses a variety of methods, materials, and applications. AM, which includes **3D printing**, has several uses in manufacturing operations, such as generating **prototypes** and **tooling**.

Traditional manufacturing often uses processes, such as **machining** and **grinding**, to remove material to create a finished product. In contrast, additive manufacturing joins materials together, usually layer-by-layer, to create a final product. Using AM, engineers create a part design and then convert it to a **three-dimensional** (3D) computer model. An AM machine turns the computer model into a finished part by stacking and joining layers of material. **End-use** AM parts often have improved complexity and functionality compared to traditionally manufactured parts.

AM processes can use polymer, metal, ceramic, and composite materials.

Additive manufacturing is a highly dynamic field. **AM** methods and applications are constantly evolving as manufacturers develop new AM-compatible materials. Most AM processes use materials that fall into one of two categories: **polymers** or **metals**. However, some AM processes can use **ceramics** and **composites**. Each material possesses unique characteristics and **properties** that determine the specific AM process for which it is best suited. The selection of the AM process may be limited by the machinery and skilled operators in a facility, or by other factors such as cost. The selection often precedes and determines material selection.

Mechanical properties describe a material's reaction to **stress** from outside **mechanical forces** that attempt to **deform** it. Different materials display each mechanical property in varying degrees.

Strength describes a material's ability to resist various types of stress. For example, **compression strength** refers to a material's ability to resist being squeezed by **compressive stress**, while **tensile strength** refers to a material's resistance to being pulled apart by **tensile stress**. **Yield strength** is the highest amount of stress a material can withstand before permanently deforming.

Toughness describes a material's ability to absorb stress without breaking. **Impact toughness** is an important type of toughness that specifically refers to a material's ability to absorb a sudden blow. Manufacturers test a material's impact toughness by dropping a pendulum on a sample and observing the sample's reaction. Another type of toughness is **damping**, which indicates a material's ability to absorb and resist vibration.

Ductility describes a material's ability to withstand deformation. A **ductile** material can be easily shaped and drawn without breaking. In contrast, a **brittle** material breaks easily when subjected to mechanical forces and, therefore, cannot be easily stretched or formed.

Hardness describes a material's ability to resist penetration, such as being scratched or dented. Manufacturers often test a material's hardness by subjecting a material sample to stress applied by an indenter for a predetermined amount of time. After removing the indenter, they measure the size of the indention it made to determine the material's level of hardness. Hard materials are not necessarily tough. For example, some metals with increased levels of hardness and tensile strength have decreased levels of ductility and toughness.

Physical properties describe a material's **weight** and **density**, and how it responds to various external factors, such as heat, **electricity**, **magnetic fields**, and **chemicals**.

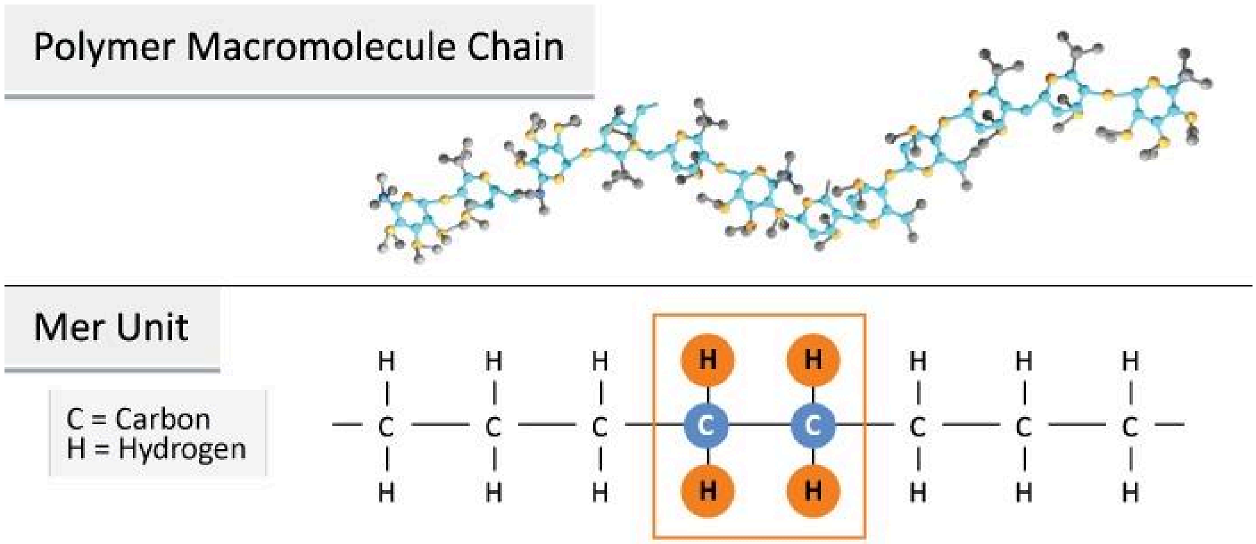
A material's electrical characteristics determine its reaction when exposed to electricity. Materials can facilitate, or conduct, electricity to varying degrees. A material's **electrical conductivity** depends on whether its **electrons** can move freely. Materials that have relatively free-flowing electrons often make good **electrical conductors**. Other materials are poor electrical conductors because their electrons are unable to move freely, so these are often used as **insulators**.

A material's **magnetism** describes its ability to attract or repel other materials. The charges of a material's electrons generate magnetic fields that flow from one **pole**, or end, of a material to the other. The opposite poles of separate magnetic materials are attracted to one another, while the like poles repel one another. Certain materials generate their own magnetic fields, others can magnetize when exposed to magnets or electricity, and some are simply not magnetic.

A material's thermal characteristics determine its reaction when exposed to heat or changes in temperature. Changes in temperature cause a different amount of **thermal expansion** in all materials. **Thermal stress**, which is caused by a material expanding and contracting, can **warp**, or distort, a material. **Thermal conductivity** describes a material's ability to conduct heat. Usually, materials that are good heat conductors are also good electrical conductors.

A material's chemical characteristics determine its reaction when exposed to environmental pollution, **oxidation**, and **radiation**. **Corrosion** is a physical and chemical deterioration that occurs in metals and ceramics due to exposure to water, oxygen, chemicals, and other elements in the environment. **Corrosion resistance** describes a material's ability to withstand the effects of corrosion.

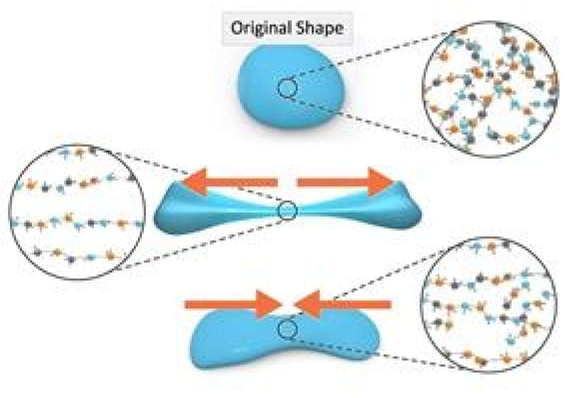
Because of the diverse mechanical and physical properties of polymer materials, the first AM processes used various polymers to rapidly build part prototypes.



Polymers consist of **mer units**, or **monomers**, which are numerous linked and repeating units of **atoms**. These atoms **bond** together to form long chains of polymer **molecules**, called **macromolecules**. One macromolecule of polymer material contains at least 100 mer units. However, most polymers contain 1,000 mers or more, and some may even approach upwards of 10,000 mers per macromolecule.

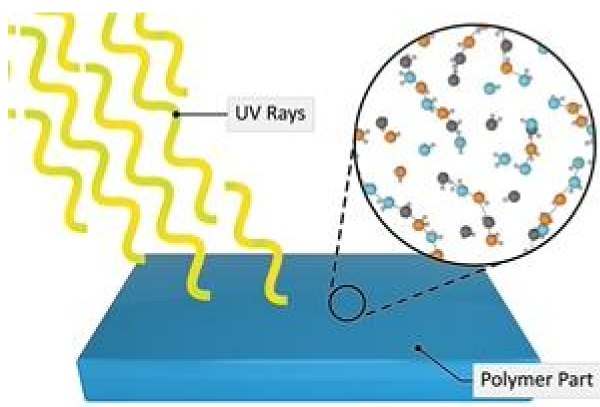
Polymer molecules can form many different configurations. A polymer's **molecular structure** determines its properties. While there are **natural polymers**, most AM methods use various **synthetic polymers**, which include **additives** to alter their properties.

Polymers display varying properties that set them apart from metals, ceramics, and composites.



Viscoelastic materials can stretch and return to their original shape.

Most polymers are **viscoelastic** materials, exhibiting both **elastic** and **viscous** characteristics. **Viscosity** measures a material's resistance to flow and is usually affected by temperature. For example, when a material is exposed to higher temperatures, its viscosity often decreases and its flowability improves. **Elasticity** measures a material's ability to revert to its original shape after being stretched. Elastic materials stretch or bend in response to stress but return to their original shape once the stress is removed. Most polymers exhibit viscoelasticity because they can stretch and return to their original shape in the short term but will flow and lose their shape over time.



UV exposure can lead to thermal degradation.

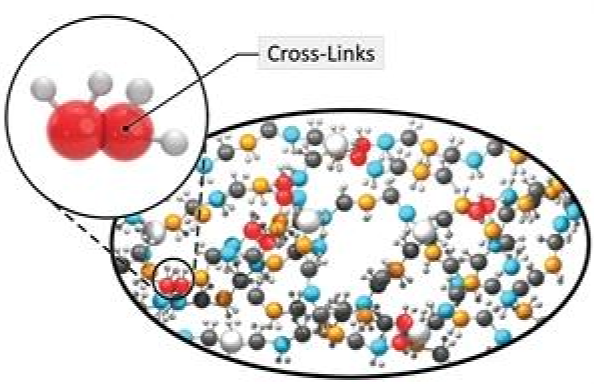
Polymers are often more susceptible to heat damage than other materials. Some materials experience **ultraviolet degradation** (UV degradation) when exposed to the sun's **ultraviolet rays** (UV rays). UV ray exposure often leads to a material overheating and experiencing **thermal degradation**, during which polymer molecules can break down. Overtime, the polymer can discolor and **fracture**. Most polymers have a high **coefficient of thermal expansion**, so they are more likely to change shape with higher temperatures. UV ray exposure can also weaken a polymer's **atomic bonds**. If these bonds break, then oxidation, another form of material breakdown, may occur.

Polymer materials fall into one of two groups based on their molecular arrangement. The first group consists of **thermoset** polymers, which are either **liquid** or **solid** at room temperature.

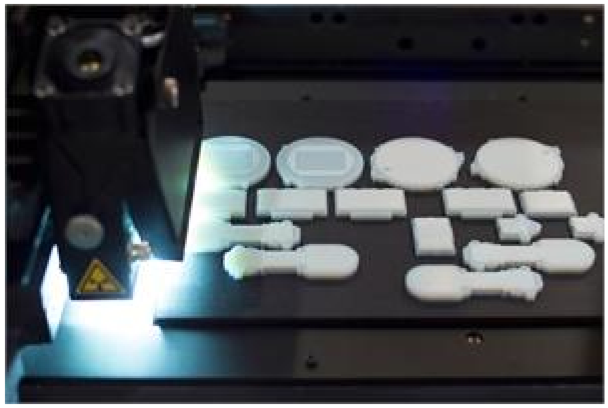
A thermoset consists of long monomer chains connected by a type of strong **primary bond**, called a **covalent bond**. Manufacturers prepare a thermoset **resin** for manufacturing by providing **reactive sites** in two different areas of the monomer chain. These reactive sites allow the thermoset resin to undergo **curing**, a process that uses heat, **pressure**, or **ultraviolet radiation** (UV radiation) to initiate **cross-linking** between multiple molecule chains. Cross-linking prevents individual chains from moving freely and independently from one another. Upon cooling, the thermoset resin creates a permanently solid **3D** structure.

Due to their cross-linking, thermosets can be heated, cooled, and formed into shape only once. Any additional exposure to heat will **char** the thermoset part.

The degree of cross-linking determines a thermoset's properties. Increased cross-linking results in a stronger polymer that resists damage from many chemical and environmental elements. Thermosets generally also have high levels of strength, **rigidity**, and **heat resistance**.



Thermoset molecule chains form cross-links.



AM thermoset parts are cured with UV light.

Thermoplastics are usually solid at room temperature and have lower processing temperatures than thermosets, allowing them to melt or soften easily when heated.

Thermoplastic molecules are held together by **secondary bonds**, which typically have very little cross-linking. As a result, thermoplastic molecules move freely when heated, and more space exists between the molecules as they untangle. As they cool, the molecules form different arrangements. Secondary bonds give thermoplastics a lower **melting point**, greater **softness**, and less rigidity than other materials, such as metals or ceramics. Thermoplastics are easily shaped through **molding** or other **shaping processes**, and they retain their desired shape after they cool.

Thermoplastic polymer molecule chains have two different arrangements: a **linear arrangement** or a **branched arrangement**. A linear arrangement consists of a long, flexible, chain of monomers that connect end-to-end with each other. Chain length affects a polymer's strength, with longer chains resulting in stronger materials. A branched arrangement consists of smaller chains of mer units that attach themselves to a longer polymer chain at irregular intervals, forming tree-branch configurations. A branched arrangement results in a thermoplastic with a lower density and melting point but a higher viscosity and level of toughness than thermoplastics with a linear arrangement.

There are two groups of thermoplastics. The first group, **amorphous thermoplastics**, have **amorphous regions** consisting of molecule chains, and sometimes branches, that are usually large and complex. These chains are randomly ordered and coiled, often intertwining with one another, which allows more room for heated molecules to move around. As a result, amorphous thermoplastics have a **glass transition temperature** rather than a true, defined melting point, so they soften gradually and become more **pliable** when heated and have a lower viscosity with higher temperatures. After heating, amorphous thermoplastics typically cool into a **transparent** material.

The second group, **semicrystalline thermoplastics** have both amorphous and **crystalline regions**. A crystalline region consists of small and simple molecule chains that are usually structured and form regular, repeating patterns. Semicrystalline plastics have tightly packed molecules connected by stronger bonds that restrict molecular movement. As a result, semicrystalline thermoplastics have a higher melting point rather than a glass transition temperature. Additionally, due to the presence of crystalline regions, semicrystalline thermoplastics are higher in both strength and rigidity than amorphous thermoplastics.

Most thermoplastics have a high **molecular weight**. High molecular weight results in a strong and **stiff** material. However, high molecular weight can also result in a higher viscosity, decreasing the flow of a material during manufacturing. After a thermoplastic cools and solidifies, manufacturers can heat and form the material for a **secondary shaping process**. This is a continuous cycle, so thermoplastics can be repeatedly heated and cooled with minimal effect on end-property performance. As a result, thermoplastics can be reused and recycled, extending their use.

While AM processes can utilize a vast array of polymer materials, manufacturers often use certain thermosets and thermoplastics more frequently than others.

Most AM thermosets are **proprietary photopolymers** that mimic the specific properties of other polymers. For example, some proprietary thermosets possess the properties of **polypropylene** (PP), so they are economical, low-density polymers with high toughness, flexibility, and **fatigue resistance**. Other proprietary thermosets mimic the properties of **polyethylene** (PE), resulting in relatively inexpensive polymers that have good ductility and impact strength as well as excellent chemical and electrical resistance. Manufacturers design such proprietary thermosets with specific properties that are ideal for an array of AM applications.

Other AM thermosets also include **polyurethanes** (PU), **polyimides** (PI), and **ultraviolet-curable** (UV-curable) **epoxies**. Polyurethanes are wear-resistant materials that are used in a variety of applications, such as molds for both electrical and automobile parts. Polyimides are lightweight, flexible materials that have excellent heat and chemical resistance. As a result, these are often ideal for use in AM electrical applications. Finally, UV-curable epoxies are tough, heat-resistant materials with high chemical resistance. AM manufacturers sometimes use UV-curable epoxies to create devices used in the aerospace, medical, and electronic industries.

Acrylonitrile butadiene styrene (ABS) materials are versatile, lightweight thermoplastics that exhibit excellent toughness as well as resistance to heat, chemicals, and impacts. Additionally, ABS has poor electrical conductivity, so AM manufacturers can use it to build insulating parts, such as electrical enclosures as well as tools used for electronic assemblies.

Polycarbonate (PC) materials are lightweight thermoplastics that offer excellent heat resistance and impact strength. As a result, AM manufacturers use polycarbonates to build parts that offer protection from exposure to high temperatures and impacts, such as medical-device casings and safety helmets.

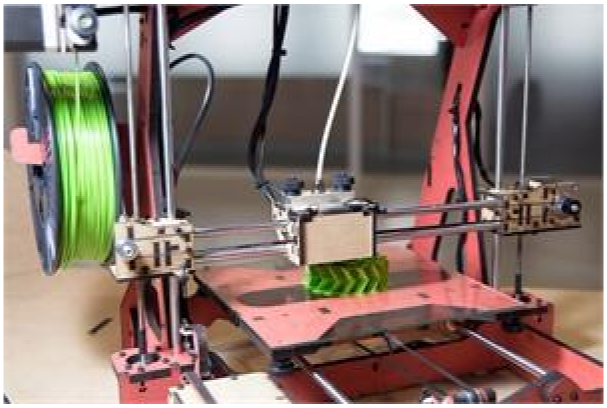
Polyamide (PA), or **nylon**, materials are exceedingly tough thermoplastics that exhibit high levels of ductility, impact strength, and **wear resistance**. Polyamides are **biocompatible** materials, which means they are safe to use with human tissues. Additionally, they can be used to build parts with excellent tolerances and surface finish. As a result, AM manufacturers often use polyamides in dental and medical applications.

Since polymers were among the first materials used in AM processes, there is a large and diverse body available to choose from when selecting a polymer for AM use. Additionally, manufacturers are constantly developing new polymers that possess unique, advanced properties.

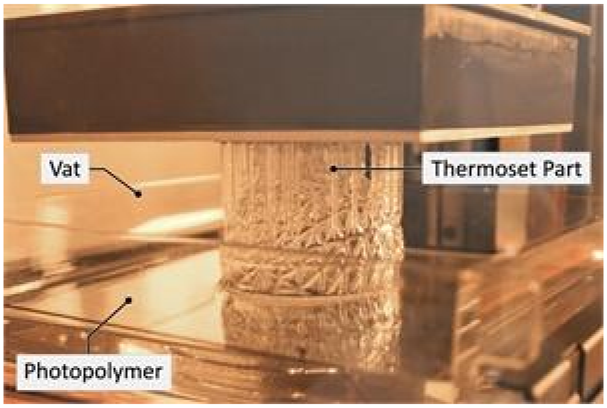
Selecting an appropriate polymer first depends on the type of AM method with which it will be used. Due to the nature of the processes, **material extrusion** exclusively use thermoplastic **filaments** or **pellets** and **powder bed fusion** uses plastic powder. On the other hand, **material jetting** and **vat photopolymerization**, both of which use curing processes, exclusively rely on thermosets.

Polymer selection also depends on the properties required for the finished part. For example, operators should consider the material's tensile strength, **moisture resistance**, and **flammability** when selecting the appropriate polymers. Additionally, selection can further be narrowed down using a material's **optical properties**, such as its level of **transparency** or **opacity**, its color, and its **index of refraction**, or the amount of light the polymer reflects.

Prior to selecting polymers, always refer to **material data sheets** and test reports provided by the manufacturer to determine its appropriateness for use in an AM process.



Material extrusion uses thermoplastic filaments.



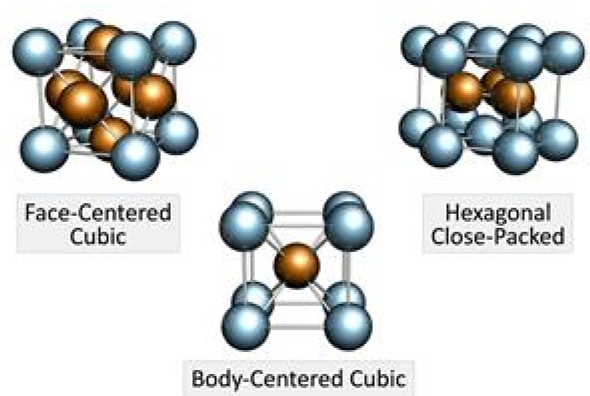
Vat photopolymerization uses thermoset materials.

In recent years, metal use in AM processes has become more frequent, and its availability continues to grow. Several metal groups, including **ferrous metals**, **nonferrous alloys**, and **superalloys**, are compatible with AM processes.

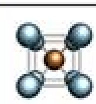
A metal consists of atoms connected by a strong, primary bond, called a **metallic bond**. Most metals are **polycrystalline**, and their molecules form **crystal structures**. There are three crystal-structure patterns, and each determines a metal's properties:

- A **face-centered cubic** (FCC) crystal structure consists of one atom at the center of each of the cube's six sides as well as an atom in each of the cube's corners. FCC metals, like **aluminum**, are often ductile.
- A **body-centered cubic** (BCC) crystal structure consists of one atom at the cube's center and an atom at each corner. BCC metals, like **chromium**, are usually hard.
- A **hexagonal close-packed** (HCP) crystal structure has atoms that are closely packed together in a hexagon shape. HCP metals, like **titanium**, are often brittle.

Solid metals possess a **uniform** crystal structure pattern, but they lose these structures when heated, allowing them to be shaped easily. As a metal cools, its crystal structures start to reform upon reaching its **recrystallization temperature**.

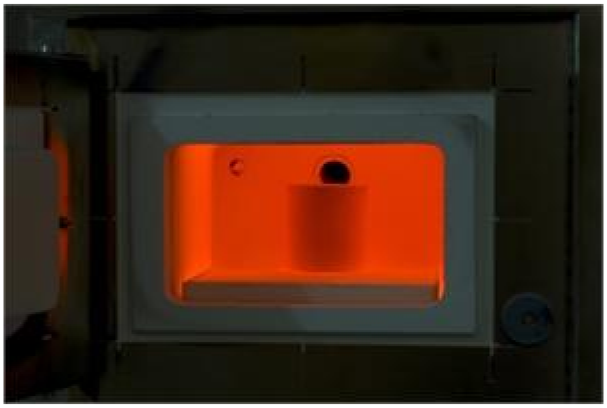


Crystal Structure Patterns

Crystal Structure		Metal Example	Common Properties
Face-Centered Cubic		Aluminum Gold Copper	Ductile
Body-Centered Cubic		Tungsten Iron Chromium	Hard
Hexagonal Close-Packed		Titanium Magnesium	Brittle

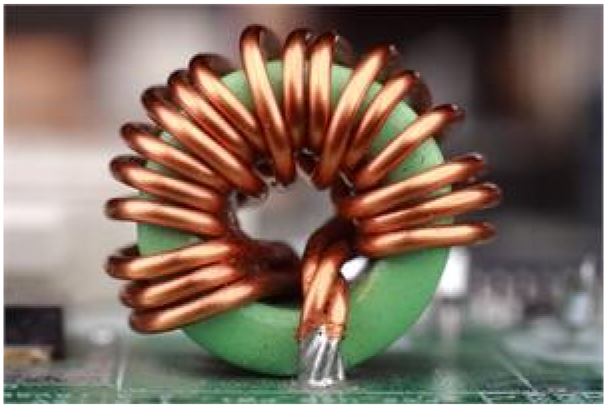
Crystal Structure Properties

Although every metal is different, most metals share common mechanical and physical properties that differentiate them from other materials, such as polymers and ceramics.



Heat treatments can adjust some metals' mechanical properties.

Oftentimes, ductility, hardness, and strength are a metal's most important mechanical properties, and many have varying degrees of each. For example, more ductile metals, like **copper**, are easily shaped without breaking, while most **steels** are relatively hard and can withstand denting and scratching. Metals also vary in their levels of strength. However, unlike polymers, metals also have varying degrees of **hardenability**. Manufacturers can use **heat treatment** processes, such as **annealing**, **quenching**, and **tempering**, to adjust the hardness of certain metals.



Copper is used in many electrical applications due to its high conductivity.

Metals exhibit extraordinary diversity among their physical properties. Most metals conduct heat well, allowing heat to flow through them relatively freely. Additionally, metals often have good electrical conductivity. In fact, some metals, like copper, are often used in electrical applications due to their high electrical conductivity. Some metals have strong magnetism and can act as **electromagnets** when exposed to electricity or other magnets. Some metals are highly susceptible to corrosion. Metals that are highly magnetized or have low corrosion resistance can be alloyed or coated to adjust these properties and resist damage.

Steels are popular commercial metals that consist of **iron** and **carbon** as well as a small amount of other **alloying elements**. The percentage of carbon and additives determines each steel variety's properties. The most common AM steels are **tool steels**, **stainless steels**, and **maraging steels**.

Tool steels are exceedingly strong due to high carbon levels. Tool steels are wear resistant, hard, and tough. Manufacturers often use AM tool steel parts for tooling, such as molds, **dies**, and **master patterns**. Manufacturers also use AM tool steels to repair die and mold tooling.

Along with various amounts of **nickel**, **manganese**, and **nitrogen**, stainless steels contain high levels of chromium, which provides superior corrosion resistance. Stainless steels also exhibit excellent strength and ductility. AM manufacturers often use stainless steels to create corrosion-resistant tools, such as **scalpels** or those used in **injection molding**.

Maraging steels, a special group of low-carbon steels, are exceedingly strong, tough, hardenable, and wear resistant. Instead of high carbon levels, maraging steels contain metallic **precipitates**, which provide hardness and strength. These steels also contain nickel along with lesser amounts of **cobalt**, **molybdenum**, and **titanium**. AM manufacturers often create maraging steel parts for use in tooling applications, such as injection molding and aluminum **die casting**.

AM metal processes create hard tooling out of metal powders.

Stainless steel AM parts are used in medical applications due to their corrosion resistance.

Compared to steels, nonferrous alloys are usually either lighter, better at conducting electricity, stronger at high temperatures, or better at resisting corrosion. Nonferrous alloys for AM processes include **aluminum alloys**, **titanium alloys**, and **copper alloys**.

Aluminum alloys include **aluminum-silicon alloys** and **aluminum-silicon-magnesium alloys**. Aluminum, a common, inexpensive nonferrous metal, is soft and ductile. Adding alloying materials, such as copper, magnesium, manganese, silicon, and **zinc** to plain aluminum increases the alloy's strength, electrical conductivity, and corrosion resistance. Although aluminum alloys are not as strong as most **grades** of steel, they often have a higher **strength-to-weight ratio**. These properties make aluminum alloy parts ideal for use in the automotive, electronic, and aerospace industries.

Titanium alloys include various **titanium-aluminum-vanadium alloys**. Titanium is a biocompatible, lightweight metal with high strength and excellent thermal, corrosion, and fracture resistance. As a result, titanium alloys are strong, lightweight, and have an excellent strength-to-weight ratio and low coefficient of thermal expansion. Alloying titanium with a variety of materials allows the titanium to undergo **precipitation hardening** as well as either increases or decreases its ductility. Additive manufacturers typically use titanium alloys for applications requiring high-performance parts, such as those used as medical **implants** or those for use in aerospace applications.

Copper alloys include various **bronzes**. Copper, a reddish metal, offers high ductility, thermal and electrical conductivity, and corrosion resistance. **Tin** is the most common alloying element in bronze although aluminum and silicon may also be used. These alloying elements can provide the alloy with greater strength, toughness, stiffness, and fatigue resistance. As a result, manufacturers sometimes use AM processes to create a variety of copper alloy parts, including **electromechanical** components and tool **cooling channels**.

A superalloy is a complex metal with superior hardness and strength as well as exceptional thermal, corrosion, and creep resistance. Most superalloys are proprietary materials that manufacturers designed for specific, advanced applications in aerospace, **biomedical**, or **nuclear power** industries.

The two most common superalloys used in AM are **cobalt-chromium-based superalloys** and **nickel-based superalloys**. Both may also contain various combinations of titanium, molybdenum, aluminum, tungsten, **tantalum**, and **niobium**. Cobalt-chromium-based superalloys are highly corrosion- and wear-resistant, non-magnetic metals that exhibit excellent

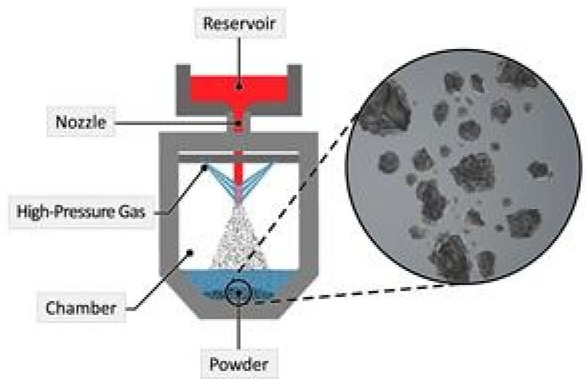
biocompatibility. As a result, they are often used in medical and dental applications. Nickel-based superalloys provide a good balance of tensile strength, **creep strength**, and **rupture strength** and exhibit superior resistance to heat, fatigue, and corrosion.

Inconel is a family of superalloys commonly used in AM. In addition to nickel, a strong, nonferrous metal with good corrosion and heat resistance, Inconels also contain chromium, improving their hardenability and wear resistance. As a result, Inconels are highly resistant to heat and corrosion, including oxidation, and maintain their high level of strength in extreme temperatures. Because of this, Inconel parts built with AM are frequently used in aerospace and **cryogenic** applications.

AM processes create dental parts with cobalt-chromium based superalloys. Courtesy of EOS.

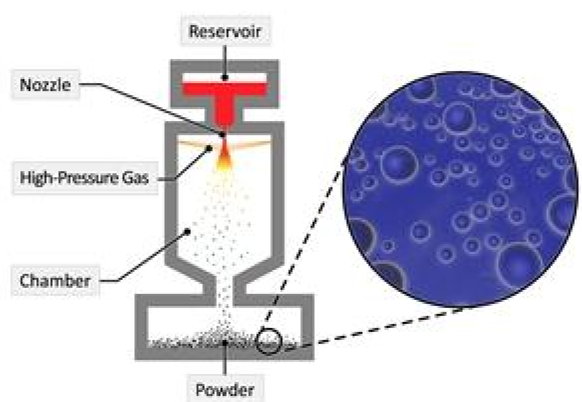
Nickel-based superalloys are often used to make turbines.

Most metal AM processes use metals in powder form. Most manufacturers rely on one of two **atomization** processes: either **water atomization** or **gas atomization**.



Water Atomization

During the water atomization process, manufacturers melt metal stock in a reservoir above a tall chamber. As the liquid metal passes through a nozzle at the bottom of the reservoir and into the chamber, a high-pressure water stream breaks the metal into small droplets that rapidly quench and solidify into powder. Water atomization is the least expensive process because of water's relatively low cost, availability, and recyclability. It can be used for most AM metals except for **reactive metals**, such as titanium alloys. However, compared to gas-atomized powders, water atomization often produces tough metal powders that have a larger, irregular shape and a relatively high **impurity** and surface-oxygen content.



Gas Atomization

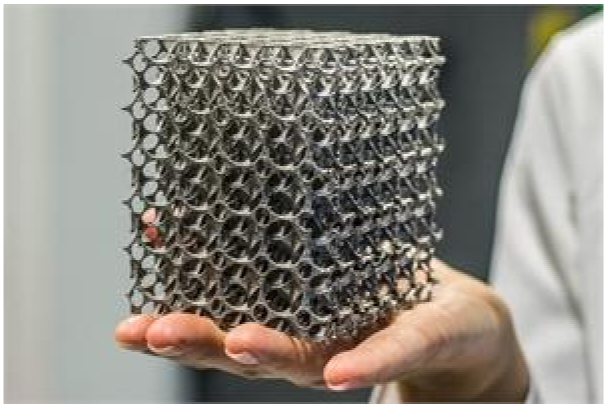
Manufacturers use gas atomization for reactive metals and superalloys. Like water atomization, the process starts with a reservoir of liquid metal located above a vertical chamber. However, as the liquid metal exits the reservoir's nozzle, a high-pressure stream of **inert gas**, such as nitrogen, **helium**, or **argon**, contacts the liquid metal, breaking it up into fine droplets. Gas atomization produces **spherical** metal powders that are more uniform in size with smaller diameters and have a lower surface-oxygen content than water-atomized powders. However, gas atomization is a more expensive process due to the additional equipment necessary to control gas pressure as well as safely store pressurized gases.

As with polymers, only certain AM processes can use metals. Powder bed fusion, **binder jetting**, and **sheet lamination** processes can all utilize metal powders, while **directed energy deposition** (DED) processes can use either metal powder or wire. **Ultrasonic consolidation** (UC) uses metal tape.

In general, AM metal powder systems, especially powder bed fusion, perform best and produce high-quality parts when using a high-quality metal powder. High-quality powder has a uniform particle size and spherical shape. Unlike irregularly shaped and sized powder particles, small, spherical particles pack more tightly into a **powder bed** and achieve a flatter, more level surface, which is important for reducing a part's **surface porosity** and increasing density. Higher levels of surface porosity reduce a metal part's fatigue resistance since **defects**, such as **cracks**, often begin to form at these areas of surface porosity. Particle shape and size also influences the powder's flow characteristics and each layer's ability to **fuse** to the next layer.

While DED systems can utilize metal powders that have a more irregular shape and size, it is more likely that a finished part may not meet its specifications when using a powder that is not high-quality. The powder's oxygen and impurity content also affect the level of its quality.

Metal AM processes include powder bed fusion methods.



The quality of AM metal parts often depends on the quality of metal powder.

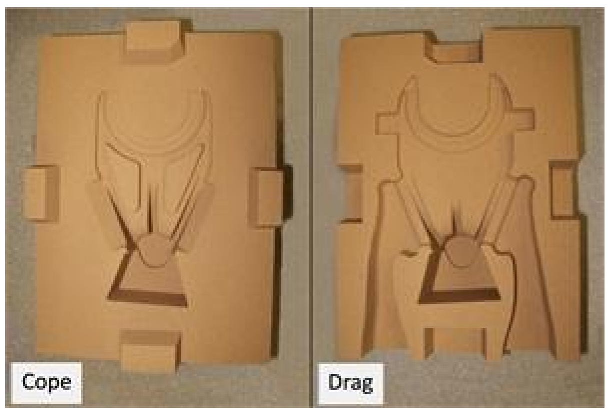
While polymers and metals make up most of AM materials, other materials are available, such as ceramics and sand. A ceramic is an **inorganic compound** consisting of metallic and nonmetallic atoms. Common AM ceramic materials include **metal oxides**, **nitrides**, **carbides**, **graphites**, and **glasses**.

Ceramic molecules are held together by two strong primary bonds: covalent and **ionic bonds**. Ceramic molecule chains create **crystalline**, polycrystalline, or amorphous structures. Most ceramics are polycrystalline, consisting of various interwoven crystal patterns and grains. A ceramic's crystal structure is often complex because it contains atoms of varying size. The ceramic manufacturing and heating processes usually determine the type of molecular structure.

Most ceramics offer exceedingly high levels of hardness, surpassing even those of steel. Despite their increased hardness, ceramics often weigh less than most metals. Almost all ceramics are very brittle with very low levels of toughness. As a result, ceramics often have poor tensile and **shear strength**, but their compression strength is usually better. Ceramics are poor conductors, but offer excellent resistance to wear and corrosion, and many can withstand extreme temperatures and adverse environments. Ceramic parts made with AM are most frequently used in dental and medical applications.

Sand is also used in some AM processes, especially binder jetting. Operators usually work with **green sand**, a material consisting of natural sand mixed with additives, such as clay, coal, and water. Sand binder jetting is often used to create molds that are then used to manufacture metal parts. These molds allow for complex geometric shapes while also being low cost.

Ceramic materials include oxides, nitrides, carbides, and graphites.

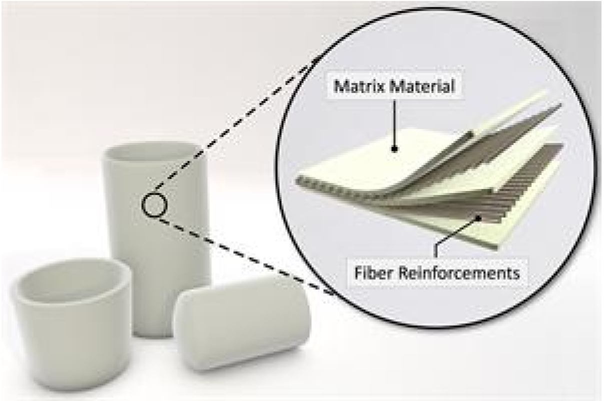


Sand binder jetting is used to create molds.

A composite is a **hybrid material** that consists of at least two materials, each from a different material group. The **matrix**, or base material, binds together **reinforcement** materials, which are either **particles**, **whiskers**, or **fibers**. Depending on their matrix material type, composites fall into one of three different groups: **polymer matrix composites** (PMCs), **metal matrix composites** (MMCs), or **ceramic matrix composites** (CMCs).

Because a composite is a **mixture** of two different materials, it frequently has properties that are superior to those of each individual material. For example, many composites possess a metal's strength, a polymer's light weight, and a ceramic's rigidity. Additionally, composites often have a high strength-to-weight ratio, excellent corrosion and fatigue resistance, and natural damping abilities.

Composite use in AM is a relatively recent development, so possible AM composite applications are still emerging. Manufacturers have used PMC materials for rapid prototyping and tooling applications, and they have begun using MMC materials in automotive applications. CMC use in AM is even newer than PMC or MMC use, and researchers are exploring future applications for additively manufactured CMC parts.



Composites consist of matrix and reinforcement materials.

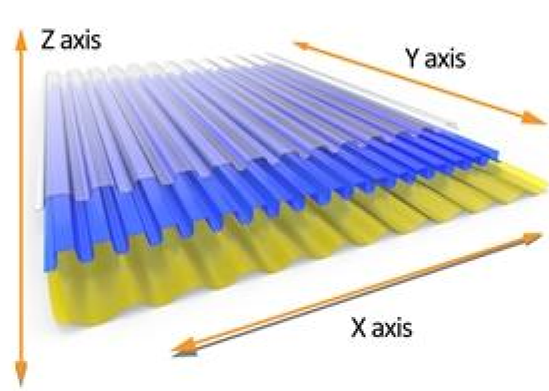
AM processes can build parts using polymer matrix composites.

Ceramic, sand, and composite materials can be used in powder bed fusion and binder jetting AM processes, while composites can also be utilized in material extrusion, material jetting, and vat photopolymerization processes.

When choosing a ceramic material for use in an AM process, one of the primary considerations includes the type of **finishing process** the material requires. For example, a ceramic material usually requires a **firing** process for a ceramic part to reach its full strength as well as to eliminate any porosity and create a fully dense material.

For composites, it is particularly important to consider the final part's required mechanical properties. For example, long, fiber reinforcements help to increase a composite material's tensile strength, hardness, and rigidity. However, reinforcement fibers are difficult to use in most AM processes, so many use reinforcement particles instead. Additionally, reinforcement materials are unable to cross between each progressive layer built during an AM process. As a result, a finished composite part may exhibit improved mechanical properties **horizontally** along the part's **X axis** and **Y axis**, but these improvements do not present themselves **vertically** along the part's **Z axis**.

Powder bed fusion can be used to make AM parts out of either ceramic or composite materials.



Composite reinforcements do not cross over layers along an AM part's Z axis.

221: Integrating Additive Manufacturing with Traditional Manufacturing

Traditional manufacturing refers to any production processes that use **molding**, **forming**, or **subtractive manufacturing**, such as **metal cutting** or **grinding**, to create a finished part. All of these processes involve either shaping or removing material from a **workpiece**.

Traditional manufacturing methods have been used for hundreds of years and offer excellent **production rates**, part **tolerance**, and **repeatability**. Improvements in traditional manufacturing technology allow for the **mass production** of parts in high volumes to meet the demands of an increasing consumer base.

Despite these advantages, traditional manufacturing has a number of drawbacks that restrict innovation in part **design**. For example, most traditional manufacturing processes can only create finished products with limited **part complexity**. A newer form of manufacturing, known as **additive manufacturing** (AM), is helping to improve upon the limitations of traditional manufacturing.

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Metal Cutting

Traditional manufacturing produces parts with excellent tolerance.

Unlike traditional manufacturing where material is removed or reshaped, **AM** involves creating parts through the addition of material. Creating parts by adding material leads to a number of advantages, including allowing manufacturers to focus on part **functionality** and create parts with increased complexity and **part integration**.

AM builds a part layer by layer.

Some manufacturers may use AM to support traditional manufacturing through **rapid prototyping**, the creation of **tooling**, such as **jigs** or **fixtures**, or through secondary processes, such as creating unique part molds. Manufacturers can use AM to create a smaller part that is then combined with traditionally manufactured parts to take advantage of both types of manufacturing. Additionally, manufacturers can use AM to create **end-use** parts for manufacturers or consumers. AM processes do have some drawbacks, particularly slow production rates, or **build rates**, so combining AM and traditional manufacturing helps optimize the efficiency and final product of an operation.

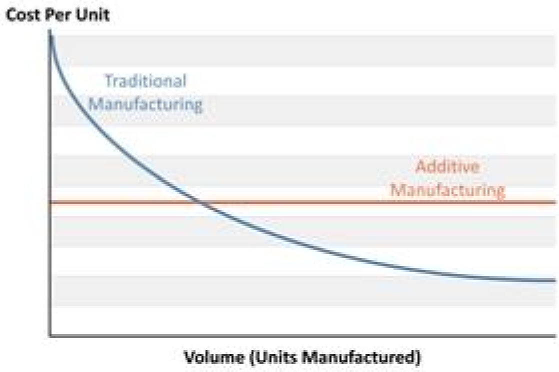
There is a wide range of AM processes, each with unique advantages and disadvantages. The AM process that is best suited for a particular manufacturer's needs will vary depending on the desired role of AM in the production process and the materials the manufacturer uses. For example, finished parts for some processes may have low tolerance or require extensive **post-processing**.

The most common AM processes fall into seven general categories. **Material extrusion** involves forcing heated material through **nozzles** and stacking layers on top of each other to create **plastic** parts. There are usually two nozzles, one to dispense build material and one to create support structures. **Vat photopolymerization** methods use **ultraviolet** (UV) light to selectively **cure liquid photopolymer**, or **resin**, and form detailed plastic parts. **Powder bed fusion** (PBF) processes use a precise heat source, often a **laser**, to **fuse** layers of **powdered** material into parts with good **strength**. **Material jetting** uses a **printer head** to deposit layers of liquid photopolymer, which are instantly cured using a UV light. **Directed energy deposition** (DED) systems use a laser to melt powdered metal or metal wire and layer it on a **build platform** where it solidifies as a part. In **binder jetting**, a printer head deposits layers of a **binder** in a bed of powdered material to build a part. Binder jetting can use a number of materials, including plastic, **metal**, and **ceramic**, but finished parts can be **brittle**. **Sheet lamination** describes a process in which a **feedstock roll** is fed onto the machine's build platform in separate sheets which are bonded together. Sheet lamination can use a variety of different materials and bonding methods to create parts. The materials are cut into the shape of the part with subtractive manufacturing methods.

Combining traditional and additive manufacturing has a number of advantages, in particular improving part functionality and speeding up **product development**. However, incorporating AM into a traditional process can require manufacturers to make large adjustments to the manufacturing system. Manufacturers must acquire new tools, train **engineers** and **operators** to use new equipment, and develop new safety protocols. Manufacturers must also train engineers to take full advantage of the flexibility and innovation allowed through **design for additive manufacturing** (DFAM).

The degree to which traditional manufacturers will have to reorganize their system to integrate AM depends on the desired AM use. Using one small AM machine as a rapid prototyping tool will require fewer adjustments, but it will not take advantage of all possible AM uses. Integrating several larger machines that can create end-use parts will require large-scale reorganization and retraining but will allow for more part innovation and cost-effective **small-batch runs**. Small-batch runs with AM are cost-effective because AM product development is less expensive, and AM production costs do not vary greatly depending on the number of parts created. Traditional methods have high product development costs, making small-batch runs more expensive, but mass-production is far more efficient than AM. Manufacturers creating end-use parts should assess product development costs and the number of parts needed in order to decide which process to use. Sometimes, AM and traditional manufacturing can be used together, with AM as the product development tool and traditional manufacturing as the production tool. In addition, manufacturers can also integrate AM into a traditional manufacturing process as part of **mass customization** or adding enhanced features.

Integrating large AM machines requires more reorganization but offers more AM opportunities.



AM costs versus traditional manufacturing costs.

Two major economic considerations for AM are production costs and manufacturing system costs. **Production costs** are expenses directly related to part creation, including initial machine purchase, machine maintenance, material costs, and other **operational costs**, such as labor and power.

Some production costs depend on the manufacturer's use of AM. Using AM exclusively for rapid prototyping will reduce the need for machine maintenance and power expenditures compared with using AM for end-use part production. Initial machine cost will also vary depending on AM usage. More inexpensive machines produce less detailed parts, often used as **visual aids**, while expensive machines produce high-quality end-use parts. A more expensive and precise machine can also make prototypes, but a less expensive machine used for prototyping cannot create end-use parts. Many AM machine manufacturers produce a range of machines, varying in cost, speed, and accuracy.

Along with profitability, manufacturers should consider AM production costs compared with traditional manufacturing expenses to assess sensible AM investment. For example, since AM requires specialized materials that are not produced in high enough volumes to lower production expenses, material costs are greater for AM. However, that can be balanced with careful resource management since AM processes often produce less **scrap**. Small-batch manufacturers may find that the reduced waste of AM offsets increased material cost. One general AM advantage is **lights-out manufacturing**, after-hours part manufacture that does not require operator supervision, which saves time and reduces labor costs.

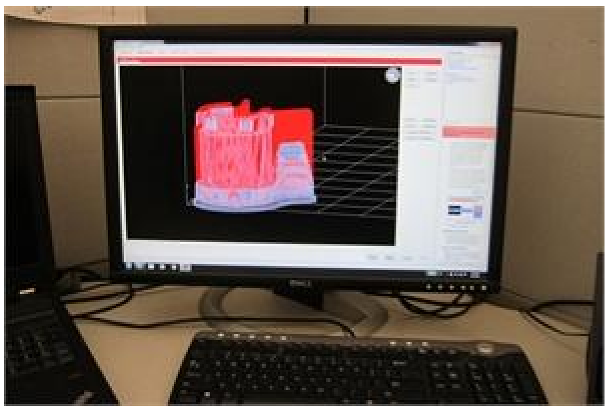
The initial purchase of an AM machine is considered a production cost.

AM requires specialized materials, such as plastic filament.

Manufacturing system costs are expenditures and other considerations related to the overall manufacturing operation, including costs associated with **overhead**, product development, and **distribution**.

In general, AM processes reduce manufacturing system costs. For example, AM streamlines new product development since engineers can quickly create and test **functional prototypes** without creating new tooling or changing machine setup. AM also reduces expenses associated with holding **inventory**. Since an entire part or group of parts can be built in one AM operation, manufacturers only need to keep build material and a computer file on hand to create a part on demand. Traditional manufacturing requires a variety of processed raw material and discrete components to create a part, in addition to the new machine setups needed to create each part. Additionally, AM machines often take up less space than traditional manufacturing machines, reducing costs related to building space. All of these factors help decrease overhead.

However, AM currently lags behind traditional manufacturing in mass production efficiency and **quality assurance**. Traditional manufacturing processes have much faster production rates and are extremely cost-effective for quickly producing a large volume of parts. Traditional manufacturing also creates parts with more predictable tolerance, **physical properties**, and **mechanical properties**, since the AM layering process can introduce unintended **defects** and **voids**. In general, AM is a worthwhile investment for streamlining new product development, improving an existing part, and allowing manufacturers to create an optimized or customized part.



AM inventory is streamlined since part designs can be stored on a computer and built on demand.

AM is not as effective as traditional manufacturing for mass production.

AM is used to create customized robotic grippers (right image courtesy of Kuhnstoff and EOS).

Manufacturers should consider how AM will affect the flow of product development and production. AM can drastically reduce product development time. Product development time includes all the time it takes to move from the conception of an idea to the finished part. AM processes help shorten product development time through rapid prototyping and design flexibility. The downside of AM from a production standpoint is that AM processes have slow build rates and often require extensive post-processing.

Combining traditional manufacturing and AM can be helpful in balancing the strengths and weaknesses of both processes. Manufacturers can use AM processes in the prototyping phase, as well as for creating unique tooling needed for traditional manufacturing. Manufacturers can then use traditional manufacturing to actually create the part, increasing production rates and lessening the need for post-processing. Manufacturers can also use AM to create one small, particularly complex piece to be integrated with a traditionally manufactured assembly, such as unique **grippers** for traditionally made **robotic arms**, to optimize production speed and part functionality.

Unlike traditional manufacturing, AM processes require relatively few tools, which can help reduce costs associated with tooling, such as tool purchase, storage, and repair. AM tools usually fall into four categories.

Design tools are the computer programs used to create the **three-dimensional** (3D) models of the parts that will be created by the AM machine. Similar to traditional manufacturing, AM processes use **computer-aided design** (CAD) software. CAD software allows for total design freedom and is particularly well suited for AM design. Once complete, engineers convert the CAD file into an **STL file**, or another similar file type like AMF, so that it can be read by the AM machine.

The materials used in part manufacture are known as build materials. Most machines use one or two types of the same category of material, such as various plastics, but newer machines can process a larger number of materials or even different categories of materials to create **composite** parts. AM processes can use a range of materials, including ceramic and **glass**, but most build materials fall into the category of plastic or metal. Plastic build materials are available as **pellets**, **filaments**, liquids, or powders, while metals are most often available as powders or **foils**.

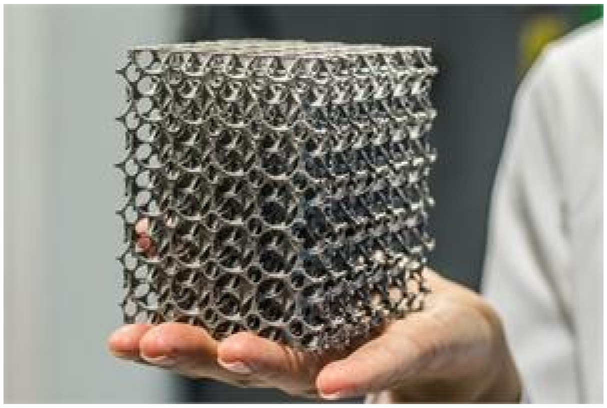
Though most manufacturers will select a machine or machines that perform one type of AM process, manufacturers who work with a range of materials may choose to incorporate multiple AM methods. The complexity of the machine is also dependent on the needs of the manufacturer. Simple machines may just allow for adjustment of layer thickness, while complex machines could allow operators to control the heat source temperature, which enables it to create material **gradation**.

Other important AM tools include post-processing tools, such as the knives used to remove support structures. In addition to build materials, post-processing tools are the most numerous and varied of the AM tools. The post-processing tools necessary for an AM operation depend on the AM process and the needs of a manufacturer. Powder bed fusion processes often require **vacuums** to remove excess powder, along with ovens for **heat treatment** and tools for **abrasive finishing**, such as a **grinding wheel**. Material extrusion processes may only require tools for abrasive finishing and painting.

Most engineers and operators who work with traditional manufacturing processes will need some form of **upskilling** to work with AM machines.

For design engineers, since traditional and additive manufacturing use **CAD** software, upskilling mostly involves learning about AM design freedom. AM parts can be much more complex than traditionally manufactured parts. AM processes can create unique and complex shapes, such as **lattice structures**, that optimize functionality and address secondary concerns, such as weight. AM also allows for increased part integration and mass customization. Despite the freedom of AM design, engineers must be aware of the limitations and challenges associated with specific methods. For example, parts made with powder bed fusion cannot have totally enclosed **cavities** as those cavities would trap excess powder. All AM methods have varying limitations for part specifications, such as minimum allowable **wall thickness** and **hole diameter**.

For machine operators, upskilling is a more straightforward process. Operators must learn to properly and safely run an AM machine. Though every machine has a unique **interface**, typically operators will need to learn how to load the STL files, set layer thickness, select part orientation, load material, and start and stop the machine. Operators may also need to remove the finished part and perform post-processing. Advanced machines, such as those capable of creating composite parts, may require more operator upskilling as well as additional training with respect to safe material handling of raw materials and finished parts.

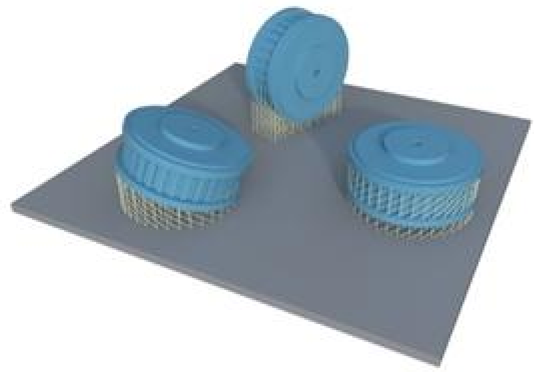


Lattice Structures

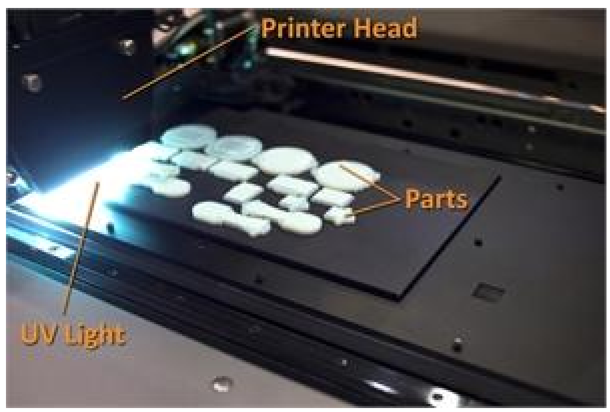
Operator using a binder jetting machine interface, courtesy of Hoosier Pattern Inc.

As there are crucial manufacturing factors in traditional procedures, such as tool **feed** and **speed**, there are also important AM **production considerations**. For example, part weight will increase as it is built, so selecting the proper **part orientation** is essential to prevent the part from **deforming** or breaking due to its weight, as well as to maximize build rate and part quality. Parts should always be oriented so that important features are built along the horizontal **X axis** and **Y axis**, as surfaces along the vertical **Z axis**, where the layers bond, will have reduced strength and surface finish. A part that is shorter than it is wide, such as a **flange** is less likely to deform and will have better tolerance if built horizontally, with the wide part flat, rather than vertically. However, a part built horizontally will likely require more support structures. **Support structures** are removable components that reinforce the part while it is being built. Because the removal of support structures can cause defects, engineers should attempt to limit the number of support structures and place them strategically, such as where they will not affect moving components. AM part orientation is highly flexible, meaning that the best solution to minimizing deformation and support structures may be to set the part at an angle. Some AM processes, such as **direct metal laser sintering** (DMLS) and binder jetting, do not require support structures.

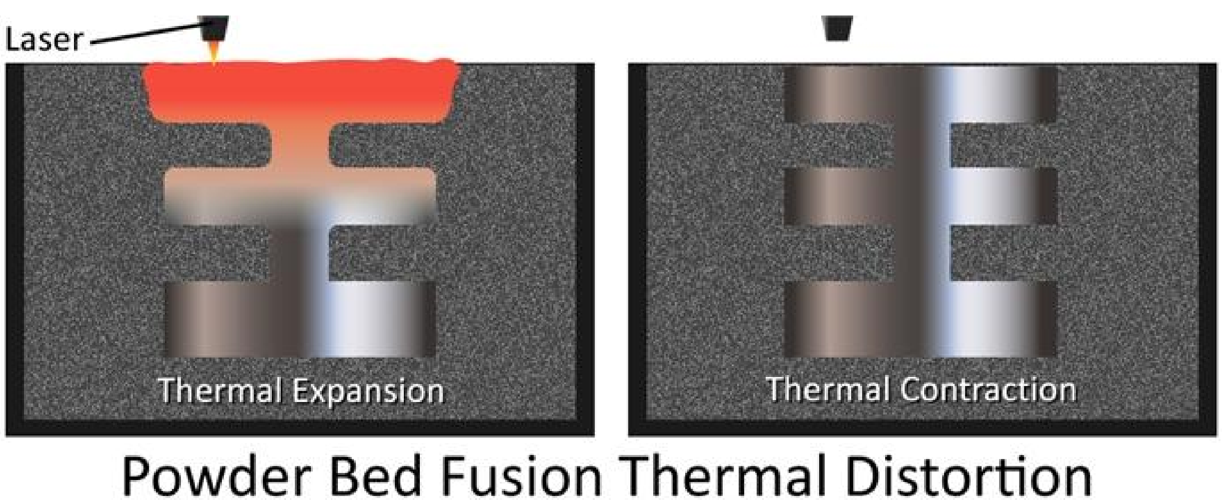
Engineers and operators must also consider part build rate. Build rate is related to layer thickness, which can be adjusted on most machines. Building with thinner layers improves the tolerance and accuracy of a part but slows the build rate. Part orientation is also a key factor in build rate, since operators can build a number of parts, similar or dissimilar, in a single operation. In vat photopolymerization, engineers can increase the build rate by placing longer support structures nearest to the recoater blade. Engineers must also balance the number of parts being built with part orientation that ensures desired part quality.



Part orientation affects placement of support structures and part quality.



Operators can select part orientation that allows them to create a number of different parts in one operation.



Other important production considerations include **thermal distortion**. Thermal distortion is the change in a part's shape or microstructure from heat exposure. Thermal distortion is a concern with AM processes that use a heat source, such as material extrusion, directed energy deposition (DED), and powder bed fusion methods. AM material layering applies heat in cycles, leading to constant temperature fluctuations. These fluctuations cause the material to expand when hot and contract when cool. Continual expansion and contraction can cause defects and voids, part **deformation**, and lower part tolerance, which are mostly concerns for end-use parts. For material extrusion, thermal distortion can be limited by reducing **deposition rate**, **layer thickness**, and **layer width**, though these adjustments will reduce build rates. Engineers can also orient parts so that layers are shorter, which reduces possible **peeling** for plastic parts. For powder bed fusion methods, engineers may select a material that is less affected by temperature fluctuation. Some metal **alloys** resist distortion better than others, for example. At some point, more advanced AM machines may be able to automatically optimize heat and air flow to prevent extreme temperature changes.

Part cleaning, courtesy of Hoosier Pattern, Inc.

For all AM processes, many parts will need some form of post-processing, such as abrasive finishing or heat treatment, after the build is complete. Post-processing refers to any procedure used to prepare a manufactured part for its intended purpose after the production process. The necessary post-processing will depend on the AM method and the desired purpose of the finished part. Material extrusion, vat photopolymerization, and material jetting parts often require less post-processing, sometimes even just support structure removal and abrasive finishing. This is also typically true for parts that will be used as visual aids or models. End-use parts and those made from powder bed fusion methods and DED often require more post-processing including part cleaning. A metal, end-use DED part, for example, may need support structure removal, abrasive finishing, heat treatment, and **cladding**. Most post-processing procedures require specialized equipment, which will add to the cost of developing an AM operation; though, again, the investment level will depend on the desired AM method and AM part usage.

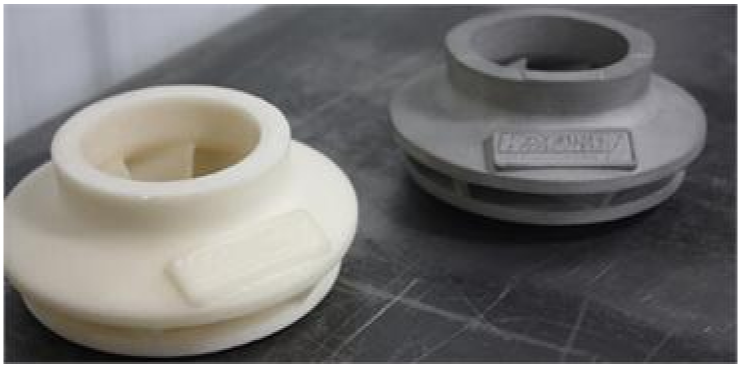
AM processes are often self-contained and pose minimal safety hazards. However, there are important safety considerations that all AM operators should follow, including the general safety procedures for any manufacturing environment.

Material handling is one of the biggest AM **hazards**. When moving heavy boxes or barrels, operators should use appropriate **lifting equipment**, such as a **forklift**, and **personal protective equipment** (PPE), such as **steel-toe boots**. In some cases, operators may handle hazardous material. In particular, powdered materials used in powder bed fusion methods can be absorbed through skin contact or respiration. Operators working with powdered materials will likely need to wear **gloves**, **respirators**, and eye protection, such as **safety goggles**.

Fumes are a concern with most AM processes. Many AM processes involve melting plastic, such as material extrusion processes, or using a **gas** to facilitate heat or light transfer from a laser. The fumes released from melting plastic or other gases associated with AM can cause **respiratory** issues, eye irritation, and headaches. In these cases, proper **ventilation** and use of **fume extractors** are essential to preserve operator safety. In small workspaces or other areas where ventilation is not possible, operators should wear respirators.

Most AM processes involve heat, meaning **fire hazards** and burns are concerns when using an AM machine. Additionally, because they are so small, powdered AM materials are **pyrophoric**, meaning they ignite very easily, even just from exposure to **static electricity**, which can be reduced through the use of **antistatic mats**. Though automated fire protection systems can be set up for lights-out manufacturing, operators should always keep **fire extinguishers** near AM machines and wear **nonflammable** clothing that covers all exposed skin. Operators should also wear heat-resistant gloves when handling any potentially hot AM components, such as a recently completed AM part or recently used material extrusion nozzles.

Post-processing procedures can also require separate safety practices. Using a grinding wheel, for example, requires safety googles or **safety glasses** to protect the eyes from flying **debris**. Removing support structures with a **chemical bath** requires proper ventilation, gloves, and safety googles. Similarly, painting, coating, and other post-processing procedures require specific safety protocols.



Prototype and Finished Part, courtesy of Hoosier Pattern Inc.

AM was originally created as a **rapid prototyping** tool and is still widely used for that purpose. Manufacturers use AM to build **conceptual models**, which provide engineers with physical examples of a part idea, or **functional prototypes**. Functional prototypes enable engineers to test the physical and mechanical properties of a part design, as well as the functionality and fit. Additionally, manufacturers can use AM to create **master patterns** for prototyping tooling, a process called **indirect rapid tooling**, allowing for quick testing of a wide range of new tool concepts.

Integrating AM as a prototyping tool into a traditional manufacturing operation is relatively simple. Generally, an operation will need just one or two machines to use AM for rapid prototyping. This small scope limits expenditures and the amount of upskilling needed. Manufacturers are then able to produce AM models, prototypes, and patterns much more quickly than would be possible using traditional methods since no new tools or machine setups are required. In some cases, manufacturers can use a specialized **service bureau** to outsource AM prototypes off-site, meaning the manufacturer will not need to integrate any AM into their on-site operation. Although design engineers must keep the limitations of traditional machines in mind, AM prototyping can also lead to innovative part development due to the design freedom of AM processes. Innovative design is especially likely to occur as design engineers become more familiar with the AM process.

Another area where AM has wide application is as a **secondary process**. A secondary process is any operation where AM is used to support traditional manufacturing, rather than to create prototypes or end-use products. One example is using AM to manufacture a master pattern or **mold** that will be used in a traditional manufacturing operation. Common operations that use AM as a secondary process include **casting**, molding, and forming operations, such as **stamping** and **hydroforming**. In some cases, such as **sand casting**, an AM process will be used to directly create the mold. In other cases, such as **silicon molding**, AM is used to create the pattern, which is then used to create the mold.

Similar to rapid prototyping, AM can create a wide variety of molds and patterns without the need for new tooling or machine setups. Although build rates may run slower, the design freedom of AM allows engineers to create and test a larger array of molds and patterns. Because the patterns and molds are used to create the finished parts, the design freedom of AM processes also enables manufacturers to create more complex parts with optimized functionality.

Traditional manufacturers who use AM as a secondary process may invest more time and resources compared to those who only use AM for rapid prototyping. This is true when using AM for processes that use a disposable **sacrificial pattern**, such as **investment casting**. Investment patterns are destroyed each time a part is made and can require more time and resources than a multiple use AM mold and pattern.

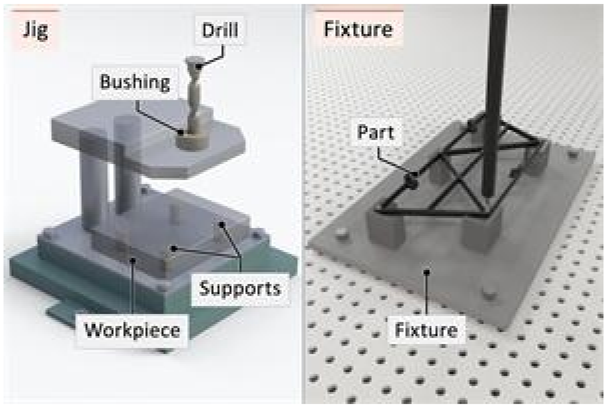
AM Mold for Sand Casting, courtesy of Hoosier Pattern, Inc.

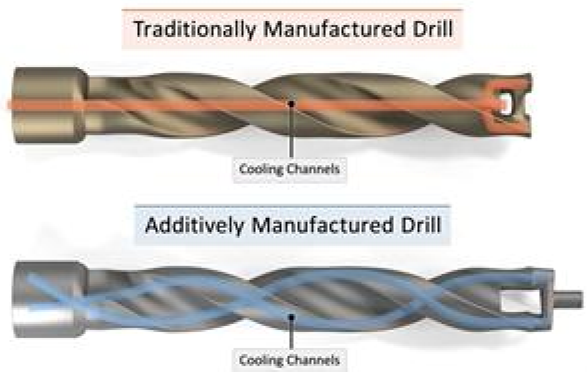
Investment Casting

Manufacturers also use AM to create **tooling** for traditional manufacturing. AM can be used to make **jigs**, **fixtures**, **cutting guides**, and other devices that help hold and position components or guide other tools. AM processes can create tooling quickly as a single, unified part, eliminating or reducing the need for assembly.

A growing use of AM tooling is creating tools that cut or shape the workpiece. In particular, manufacturers have used **DMLS** to create **drills** with optimized **internal channels** that allow for improved **cutting fluid** flow. Improved flow enhances drill performance and lengthens drill service life.

AM fabricated tooling can streamline workflow and improve part tolerance. AM can streamline the workflow by quickly producing customized and highly efficient tooling on demand. AM fabricated tooling improves part tolerance in a number of ways. Jigs ensure an assembly is held in the proper **alignment**, while cutting guides ensure all holes and other features cut into a workpiece are accurate, and AM drills generate less heat and cause less thermal distortion. AM fabricated tooling offers a unique opportunity to integrate a cost- and time-saving measure into any operation that involves part assembly or cutting.





A rapidly growing use of AM is to create **end-use**, near **net-shape** parts. End-use parts are AM components that are used directly by a general consumer. These AM components can include footwear and sporting accessories or components that industrial manufacturers will add to larger assemblies, such as automobile **drive shafts** or jet engine **turbine blades**.

Using AM to create end-use parts allows engineers to focus their design on part functionality. Since AM machines create the finished part, engineers face very little in the way of process or machine limitations compared to traditional manufacturing. Additional AM benefits include optimized **topology** and a reduction in part weight, which is particularly valuable in the aerospace and automotive industries.

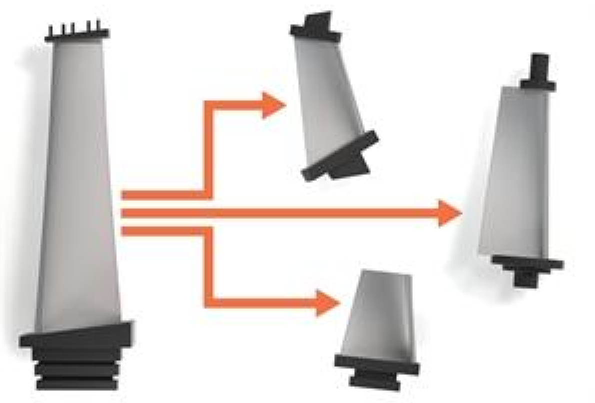
Integrating end-use AM with traditional manufacturing requires the greatest investment of time and money but potentially offers the greatest return on investment. Manufacturers may have to purchase more AM machines and upskill more engineers and operators. However, using AM to fabricate end-use products enables manufacturers to offer more complete, flexible service while still taking advantage of rapid prototyping. Using both AM and traditional manufacturing enables manufacturers to optimize part design and perform cost-effective, small-batch production, as well as mass production.

AM Sporting Goods, courtesy of Stratasys.

AM Turbine Blade

Mass customization is the ability to quickly adjust a part design so that a large number of distinct versions of that part can be manufactured to the exact specifications of a single customer or manufacturer. Traditionally, creating a custom part requires extensive changes to a machine setup and tooling, which can be time- and cost-prohibitive. AM machines, on the other hand, can create parts of any shape without the need for new tooling or machine setups. Customization with AM only requires adjusting the CAD file for a part. CAD models for mass customization can be made very simple in order to facilitate the customization process.

Although manufacturers can use mass customization for components such as customized jewelry, sporting goods, ear buds, and specialized aerospace or automotive components, it is particularly valuable in the medical fields. Medical **implants**, such as **spinal inserts**, work best when tailored to the specifications of a particular patient. With AM, a basic implant CAD design can be easily adjusted based on a scan or mold of a patient's anatomy. Engineers can use the same process to create other important medical devices such as **dental braces** and **hearing aid** components.



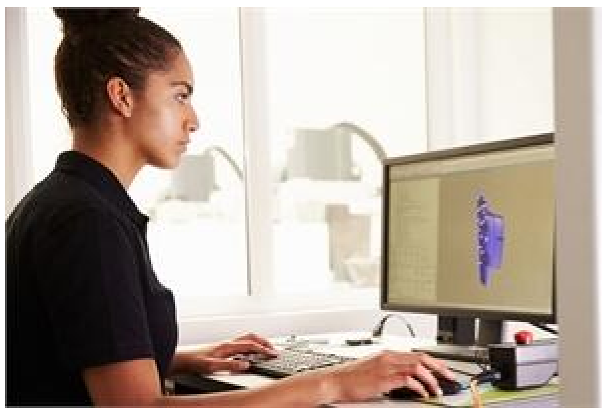
Customization of Turbine Blades

AM Spinal Insert

Setting up mass customization within a traditional manufacturing operation is somewhat similar to any end-use process. In addition to the purchase of AM machines and workforce upskilling, manufacturers must have enough engineers in place to continually adjust CAD files to customer specifications. In some industrial customization cases, such as developing specialized engine components for custom cars, engineers may work directly with the customer to augment an existing CAD file or blueprint. A system must also be in place for manufacturers to communicate with customers and transfer part specifications. This can involve investing in software that can interpret information gathered by a scanner, such as a **laser scanner**, or a mold used by the customer. For example, a customer may want to customize a mass-produced, traditionally manufactured object. The object will need to be scanned in order to create the CAD model that can be adjusted. Molds are usually used when customizing a part for the human body, such as taking a mold of a person's teeth to create custom dental braces.

Because of the complexity involved, most AM mass customization operations are created to perform one specific purpose, such as creating custom dental braces, rather than integrating them with traditional manufacturing operations. However, mass customization is an important area of growth for AM, and improving technology has streamlined the process.

Laser scanners are sometimes used in mass customization, courtesy of Hoosier Pattern Inc.



Engineers will need to be available to adjust a CAD design for mass customization.

AM Ductwork

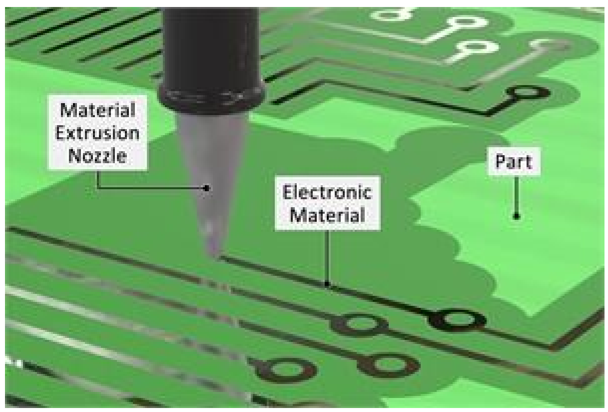
Another important advantage of AM is **part integration**. Part integration refers to taking a part that is usually created through joining a series of smaller, discrete parts and designing it, so it can be manufactured as a single, unified piece. **Ductwork**, for example, is usually created by using **mechanical fasteners** to connect a large number of metal plates or tubes, but AM ductwork can be created as one uniform piece or, at least, in larger complete sections. Part integration reduces assembly time, improves part functionality, and decreases part weight.

The ability to integrate parts is, for the most part, automatically available to any traditional manufacturer who invests in using AM to create end-use parts. The one additional consideration is machine size. Common AM design limitations include build size. Most typical machines can only create parts that are around 27 cubic feet (0.76 cubic meter) or smaller. Larger machines exist but are currently very expensive. Machine costs will likely go down over time, but manufacturers should consider if the ability to create large, integrated parts would be immediately valuable to their operation.

One exciting manufacturing development is combining AM and traditional manufacturing to create one part, often called **hybrid manufacturing**, which can perform both operations in the same all-in-one machining center. For example, manufacturers may use traditional manufacturing to create the large, relatively simple body of a **turbine disk**. Manufacturers could then use a hybrid additive and traditional manufacturing machine to add the more intricately shaped turbine blades and potentially other small, intricate **features**. With one machine, manufacturers can also use AM to build the body of a part and then introduce a traditional method to improve surface finish and tolerance, such as **milling**, or quickly create a series of uniform features, such as **drilling** a series of identical holes. A hybrid approach is particularly valuable for adding smart manufacturing components to any traditionally manufactured part. For example, an engineer can embed smart sensors using material extrusion or jetting, allowing for innovative electronic design. AM processes can also be used to repair damaged metal parts.

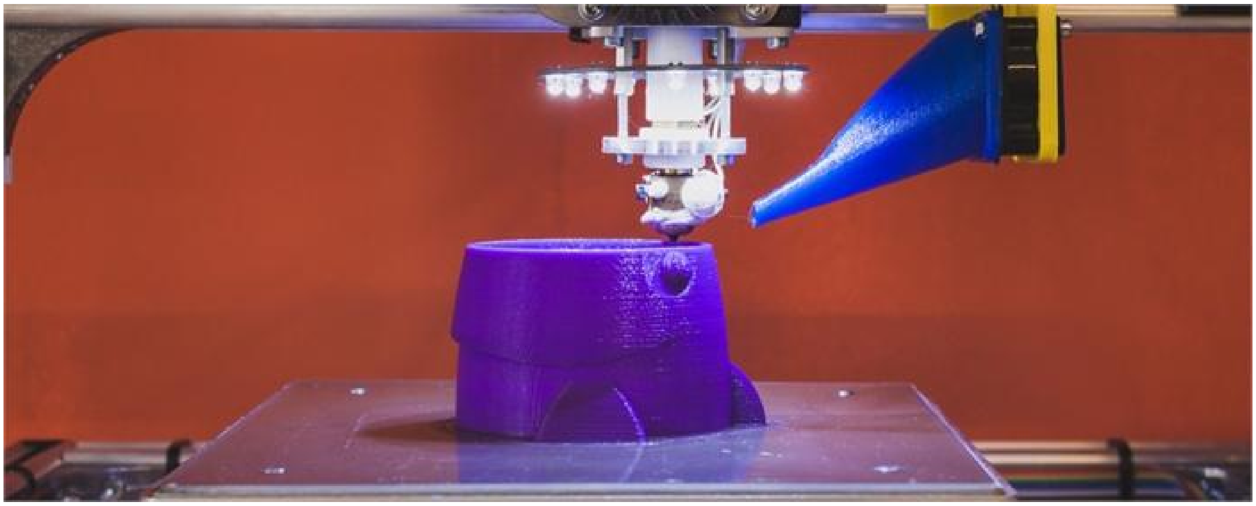
Hybrid manufacturing is a rapidly developing process. Though it may require the development of new techniques or software, traditional manufacturers integrating AM into their operation can continually experiment with hybrid techniques. DED is the most common AM operation used in combination with a traditional manufacturing method. Machines that can perform both AM and traditional operations are more expensive but efficiently take advantage of the benefits of both types of manufacturing. AM machines used with manufacturing electronics are also fairly expensive, but offer the opportunity to move electronic technology beyond its current limitations.

Drilling can be used to quickly add a series of uniform holes to an AM part.



AM electronic manufacturing.

231: Additive Manufacturing as a Secondary Process



Additive manufacturing builds parts layer by layer.

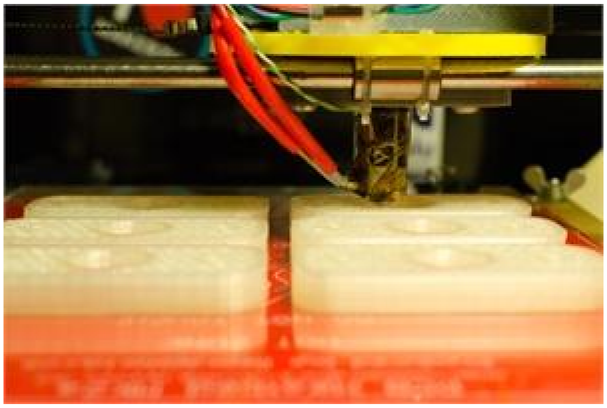
Additive manufacturing (AM) refers to a variety of processes that build **three-dimensional** (3D) parts, usually layer-by-layer, to create a final product. AM arose from manufacturers' need for **rapid prototyping**. However, since it first originated, additive manufacturing use has grown, and manufacturers are now using AM as a primary process to create many different **end-use** products for a variety of applications.

As AM use continues to evolve, manufacturers have begun applying it as a **secondary process**. In AM secondary processes, manufacturers use AM methods to produce **tooling**, such as **patterns** or **molds**, which will then be used by **traditional manufacturing** processes, such as **casting**, **molding**, or **forming**, to create a final end-use product. Since the end-use part or tool is not created via AM, AM secondary processes are sometimes referred to as **indirect rapid tooling** or **indirect rapid prototyping** processes.

There are several advantages and disadvantages associated with using **AM** as a secondary process. Manufacturers must weigh these against one another to determine whether or not AM secondary processes are worthwhile.

Traditional Manufacturing Process

Traditional manufacturing processes suffer from several limitations, such as a lack of flexibility in **part complexity** and **mass customization**. Incorporating AM within traditional processes provides manufacturers the ability to address these limitations. For example, additive manufacturing processes typically afford greater **design** freedom, giving manufacturers the ability to easily modify and customize a design. Manufacturers are also able to produce parts with greater **geometric complexity** and a variety of **features**. Additionally, most AM methods produce less scrap than traditional processes, so manufacturers are often able to minimize **waste** and even reduce production costs.



Additive Manufacturing Process

On the other hand, traditional manufacturing processes are able to create large volumes of parts, and they often have reliable **quality assurance** methods. Due to their layering processes, some AM methods can add **defects** to a part. Additionally, compared to traditional manufacturing processes, AM processes have slower **production rates**, or **build rates**. Finally, using AM as a secondary process is not always cost effective. For example, AM machines and materials are expensive, particularly because AM machines cannot produce the same volume of parts as **automated** traditional manufacturing machines.

One of the first areas in which manufacturers started to utilize additive manufacturing as a secondary process was in **investment casting**. Investment casting is sometimes referred to as **precision casting** or **lost-wax casting**.

The investment casting process begins by assembling several **sacrificial patterns** made of **wax** onto a **sprue** to create a cluster of patterns, called a **tree**. Next, the pattern tree is repeatedly dipped into a **slurry** made of **refractory**, a type of **ceramic** material, in order to coat each individual pattern. Once the slurry coating dries around the wax patterns, manufacturers place the trees into a furnace in order to melt or burn out the wax pattern and create a **sacrificial mold**. Manufacturers then slowly pour or inject molten metal into the mold, which is then broken apart upon the metal cooling and taking the mold's shape. Each metal part created by investment casting requires both a new pattern and mold.

Because it uses a sacrificial mold, investment casting is capable of producing highly complex and detailed parts that would be difficult, or even impossible, to create with traditional manufacturing processes. It is often able to be used with almost any **ferrous** and **nonferrous** metal. Additionally, parts made with investment casting typically have an accurate **tolerance** and excellent **surface finish**.

Metal Casting Process

Casted Metal Parts

Despite the multiple benefits associated with investment casting, the process does possess several disadvantages. For example, not only does investment casting require specialized equipment and materials, but it often takes several production cycles to make a pattern and mold that will eventually create a defect-free final part. As a result, investment casting is a highly time-consuming and expensive process. Manufacturers have had great success in addressing these disadvantages by applying AM as a secondary process in investment casting.

Manufacturers are able to use several different AM methods to benefit the investment casting process. **Vat photopolymerization**, **material jetting**, **binder jetting**, and **material extrusion** are all AM processes commonly used by investment casting manufacturers. However, certain AM methods work more effectively than others. For example, **powder bed fusion** is able to create partially hollow patterns out of materials that **implode**, rather than explode, during the burnout stage. Implosion lessens the chance that a sacrificial mold will develop **cracks**.

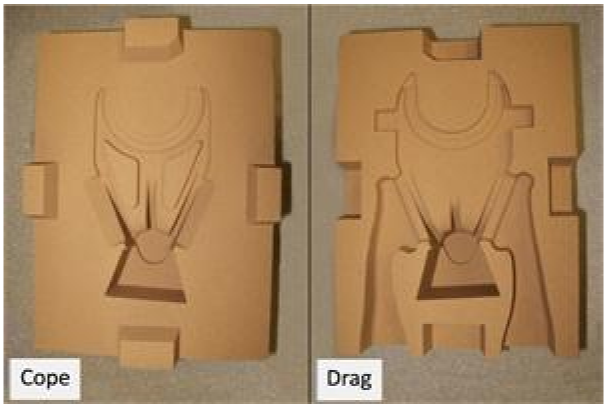
Manufacturers who use investment casting in their operations can utilize AM to **optimize** their **process development**. For example, manufacturers can use AM processes to rapidly create prototypes of patterns and molds during their initial production phases. As a result, manufacturers are able to simultaneously test and evaluate multiple designs. Additionally, by using AM processes to directly build a pattern or mold, manufacturers are able to identify any possible design issues and make necessary design modifications prior to completing a full production run. This reduces the likelihood that a final part may not function as expected, which would force manufacturers to restart their process from the beginning, and allows manufacturers to move into final part production much sooner than is possible without AM.

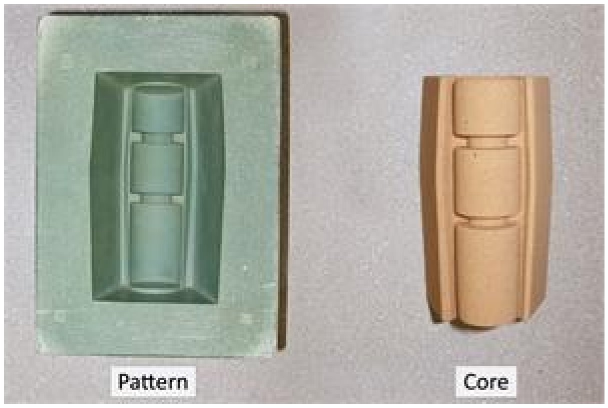
AM processes also give manufacturers the ability to use investment casting with low-volume productions. Due to the high costs associated with its process-specific tooling, traditional investment casting is often far too expensive to use for only a few hundred final parts. However, using AM to create patterns and molds reduces both time and costs. As a result, low-volume investment casting productions pose much less of a financial risk for manufacturers and can even increase their **profit margins**.

Sand casting is another **low-pressure casting** process that uses both a sacrificial pattern and a two-part sacrificial mold. The upper mold half is called the **cope**, and the lower half is the **drag**.

Sand casting processes use a mold made of **green sand**, or **foundry sand**, and a **binder** material rather than a ceramic mold. To make a mold, manufacturers first place a sacrificial pattern into a two-piece frame referred to as a **flask**. They then make a **negative impression** of the pattern by tightly packing sand around it. After removing the pattern, manufacturers add a **gating system**. Next, the flask is covered with a lid to dry and solidify the sand. Once both mold halves are dry and joined together, manufacturers can pour molten metal into the mold cavity. To create a part requiring **undercuts** or **internal cavities**, such as an **engine block** or a **cylinder head**, manufacturers place **cores** inside the mold prior to pouring the metal into it.

Sand casting is a widely used metal casting process because its production costs are relatively inexpensive compared to other processes, especially when it is utilized for low-volume productions. Additionally, it possesses the ability to create large parts out of both ferrous and nonferrous metals.





Despite their popularity, sand casting processes usually offer lower accuracy and surface finish quality than other casting processes. As a result, parts created by sand casting often require secondary **machining** processes to bring them within tolerance and improve their surface finish. Additionally, since hollow parts require the creation of cores, they can add significant costs to sand casting operations.

Manufacturers who use AM in sand casting processes often experience two significant benefits: improved part accuracy and greater part complexity. For example, the accuracy with which AM methods can build sand casting patterns and cores allows manufacturers to create finished parts with improved tolerances and surface finish. As a result, the need for secondary machining processes is often minimized, if not eliminated. The ease with which AM methods produce complex geometries also provides manufacturers with the ability to combine multiple cores into one single part. This reduces scrap and minimizes **lead times**.

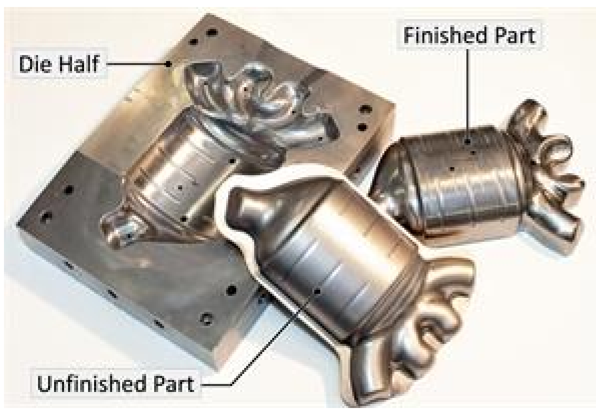
Due to recent advancements in AM technologies and materials, manufacturers can use AM methods, such as binder jetting or powder bed fusion, for rapid tooling and to directly build sacrificial sand molds without the use of a pattern. Completely eliminating the need for patterns reduces the costs associated with pattern-creation time and tooling expenses.

Unlike investment and sand casting, **die casting** is a thermal, **high-pressure casting** process that uses a reusable steel mold, called a **die**. A die consists of two parts, a stationary **cover die** and a movable **ejector die**. When joined together along their **parting line**, the two halves create a **die cavity**. Both die halves mount to a **die casting machine**. Similar to sand casting, manufacturers can utilize cores in order to create any internal features required for a part.

During die casting, manufacturers use a **pumping system** to quickly inject molten metal into a die via a system of **runners** and **gates**. The metal remains in the die cavity until it has cooled and solidified into its final shape. The die casting machine moves the ejector die in order to separate the two die halves, open the die, and eject the part from the die cavity.

Die casting is an efficient, versatile process that offers a high-degree of **repeatability**. It often produces complex parts with tight tolerances and multiple surface finish types. These parts usually do not require much machining or many finishing processes, which helps to enable quick productions.

Steel die cavity with cores.



Die casting can produce parts with good surface finish.

Applying AM as a secondary process allows manufacturers to address several limitations, such as high costs and long lead times, associated with the overall die casting process.

Die casting's initial costs are quite high since its equipment, including die production, is very expensive. Due to extreme pressures and temperatures that dies must withstand during a casting process, dies require additional machining, usually **drilling**, to add **cooling channels** before they can be used. Even with cooling channels, dies eventually **degrade** and **warp**, requiring either repair or replacement. Repairing dies requires lengthy **downtime**, while replacing dies only adds to die casting's already high costs.

Traditionally, manufacturers have used AM processes within die casting for rapid prototyping of patterns, dies, and finished parts. This enables manufacturers to avoid many design flaws or issues that might arise during production before beginning the die casting process.

The ease with which AM processes create complex parts allows manufacturers to build more efficient and higher quality dies containing **contoured cooling channels**. Traditionally machined **straight cooling channels** are often unable to reach problematic hot spots and result in uneven cooling. Contoured channels, however, allow for **conformal cooling** and

dissipate heat more efficiently and evenly. As a result, manufacturers maximize tool performance, minimize tool degradation or warpage, reduce **cycle time**, and increase part quality.

Repairing dies requires lengthy downtime, while replacing dies only adds to die casting's already high costs. Using AM metal processes, such as **direct metal laser sintering** (DMLS) or **directed energy deposition** (DED), to repair or add material to dies may significantly reduce tooling costs by extending die life and reducing die repair expenses.

Silicone molding, or **room temperature vulcanizing molding** (RTV molding), is a three-step process that manufacturers use to create **plastic** parts that the medical and **aerospace** industries often use for prototyping and testing.

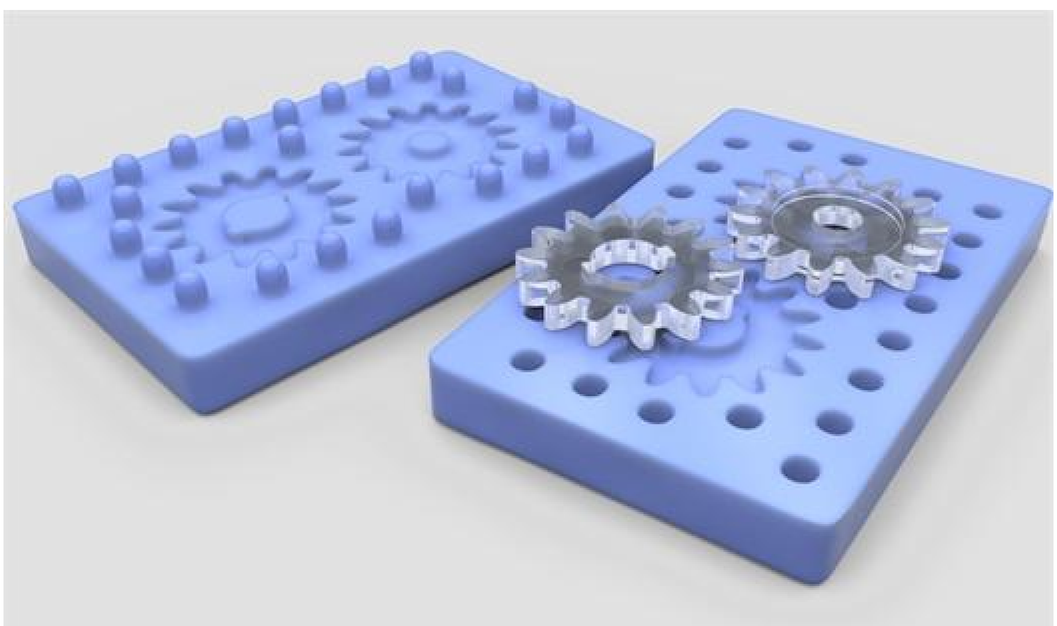
Traditionally, silicone molding requires manufacturers to first machine a highly detailed **master pattern** made out of either plastic, wood, or metal. Next, manufacturers pour liquid **silicone rubber** over the pattern and allow the material to **cure**. Curing produces a flexible, yet firm, reusable silicone mold. Manufacturers then slowly fill the mold cavity with a **thermoset** material, usually **urethane** or an **epoxy**, that hardens to produce the final product.

Silicone molding is a highly repeatable process that is capable of producing extremely complex and intricately detailed parts with tight tolerances. Due to the mold's flexibility, silicone molding better accommodates a part with internal details and undercuts than investment, sand, and die casting processes. Each silicone mold can usually produce between 25 to 50 parts before it begins to degrade. Since mold degradation can result in final parts with reduced surface finish and detail quality, silicone molding is often best for use with low-volume productions of between 25 to 100 final parts.

Silicone being poured into master pattern

Finished silicone mold after curing.

Manufacturers frequently use AM processes to reduce the cost of materials, tooling, and equipment in silicone molding production. Machining master patterns often requires long lead times and skilled employees, which only increases costs. In traditional settings, part designers may sacrifice part functionality and limit pattern complexity in order to reduce time and labor.



AM processes can easily build master patterns for more complex silicone molds.

Since traditional pattern-making processes are quite expensive and time consuming, replacing them with AM methods can streamline the silicone molding process. Material extrusion and material jetting processes are able to build master patterns out of strong, **heat resistant** materials that allow manufacturers to reuse each pattern to make additional molds. AM-produced patterns are high-quality, require minimal **finishing processes**, and are, therefore, often ready for immediate use. Since material extrusion and material jetting systems are fully automated, they require very little employee supervision. They build patterns in less than 24 hours and make implementing any design changes much easier and more efficient.

Composite molding, or **lay-up molding**, creates **high-performance composite** parts with a wide variety of applications.

Composite molding is a **manual process** that shapes a **composite** into a final part using an **open mold**. If a final part requires internal features, manufacturers use **sacrificial cores** in addition to the open mold. During composite molding, manufacturers first cover the mold and any cores with a **release agent** and **gel coating**. Once the coating cures, **reinforcement material**, frequently **fiberglass** or **carbon fiber**, is placed into the mold. A **matrix material**, usually **resin**, is then poured onto the reinforcement material until it is saturated. The application of pressure, either manually or via a **vacuum system**, removes any excess resin and air bubbles. This process repeats for each successive layer until the composite part reaches its required thickness. The part must fully cure prior to being removed from the mold and undergoing any finishing process. Curing often occurs at room temperature, but using heat lamps or an oven can quicken the process.

Due to the multiple reinforcement layers, composite molding produces exceedingly strong parts. As a result, composite molding is ideal for low-volume productions of large parts that are required to possess a high level of strength, such as **turbine blades**.

Composite molding with carbon fiber.

Composite molding with fiberglass.

Composite molding is a time-consuming and labor-intensive process, and traditional manufacturing of molds and cores presents significant limitations. However, manufacturers can use AM methods to address many of these challenges.

While molds for composite molding can be machined with **computer numerically controlled machines** (CNC machines), most manufacturers prefer to avoid the expense of CNC machines and the skilled personnel required to run them. As a result, many manufacturers hand-make molds using special **hand tools** and a master pattern, or **plug**. The manual mold-making process is similar to composite molding. Molds may require multiple design iterations to bring their parts within tolerance, adding extra time and cost to an already lengthy and expensive process.

Creating sacrificial cores also present significant challenges. Sacrificial cores are made with fragile, brittle materials that are difficult to handle, require additional machining, and are problematic to remove. In order to eliminate the need for sacrificial cores, manufacturers traditionally resort to creating a composite part in separate components. These components must then be **bonded** together, requiring additional time for **assembly**. However, this also produces a **seam** that weakens the part and requires additional machining.

Many AM methods, but most frequently material extrusion, are able to create both the molds and cores used in composite molding. Using AM can dramatically minimize lead times. Compared to traditional methods of core- and mold-making, automated AM processes are less labor-intensive and even allow for **lights-out manufacturing**. As a result, manufacturers can reduce their production costs. Since AM processes are also extremely accurate, AM methods increase mold and core accuracy and reduce the need for multiple design iterations.

Manufacturers can also utilize AM methods to create **soluble** cores rather than sacrificial cores. For example, the material extrusion process can build **thermoplastic** cores that easily dissolve when submerged in a **chemical bath** or **solvent**. Using additively manufactured soluble cores allows manufacturers to create complex, hollow composite parts without seams or the need for additional machining and assembly.

Manufacturers also apply AM as a secondary process for a variety of other forming and molding processes.

Sheet metal forming processes, such as **hydroforming**, **stamping**, and a variety of other methods, shape **sheet metal** into a final part. Sheet metal forming methods apply high levels of pressure to metal sheets and force them against a mold or die, producing parts with complex shapes and even small undercuts. While most often used for low-volume part productions, sheet metal forming is also appropriate for use in prototyping, part repair, and custom-part productions. For example, the aerospace and automotive industries use sheet metal forming methods to produce engine and suspension components.

Thermoforming shapes flat **thermoplastic sheets** into final parts. During the thermoforming process, manufacturers heat thermoplastic sheets and apply low-levels of pressure to force the sheets around an **aluminum** mold. After it is heated, a sheet remains against a mold until it cools. **Thick-gauge thermoforming** produces larger parts such as liners for pickup truck beds and casings for medical-equipment, while **thin-gauge thermoforming** produces smaller parts such as **blister packs** and disposable cups.

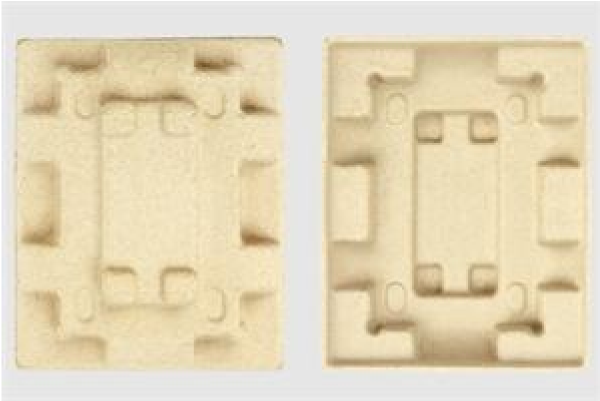
Paper pulp molding, or **fiber molding**, shapes paper pulp into final parts, such as packaging components for electronics, automotive parts, and household goods. Paper pulp molding uses a slurry that consists of newspaper and **kraft paper**, which has been ground and dissolved in water. Manufacturers submerge a mold into the slurry, use **vacuum pressure** to force the slurry material around the mold, and then add another mold that **mates** with the original mold to shape the material. Next, manufacturers remove the mold from the slurry while it is still under pressure to drain all water from the pulp. Once the water is drained, an oven thoroughly dries the part.

Traditionally, manufacturers have used a variety of machining methods and materials to produce specific molds, dies, and other tools for sheet metal forming, thermoforming, and paper pulp molding. Such methods not only require long lead times and skilled employees, but their limited capabilities often reduce a part's possible complexity.

Manufacturers often use AM to create tooling for these forming and molding operations. Doing so increases their ability to efficiently design and produce complex or custom parts and can cut lead times and production costs in half.

Since AM methods can be used with a range of materials, including **polymers**, metals, ceramics, composites, they are able to create customized tooling possessing specific mechanical properties. For example, material extrusion can build molds using **polyetherimide** (PEI), a strong polymer capable of withstanding pressures of up to 10,000 **pounds per square inch** (psi) or 69 **megapascals** (MPa). These molds are ideal for use during metal sheet forming, which uses exceedingly high pressures. However, material extrusion can also create molds using **acrylonitrile butadiene styrene** (ABS) and other polymers, which possess the **porosity** and **rigidity** required for paper pulp molding.

AM produced die and inserts.

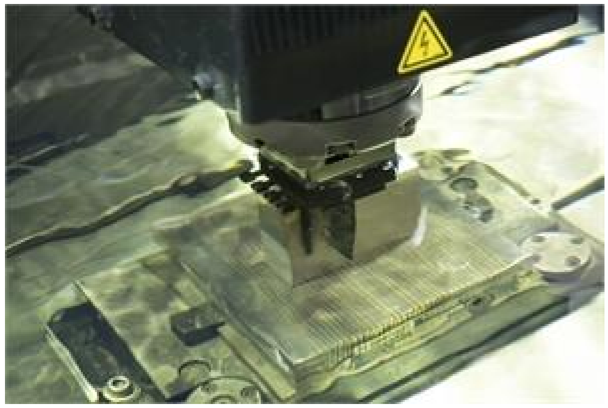


Paper pulp molding part.

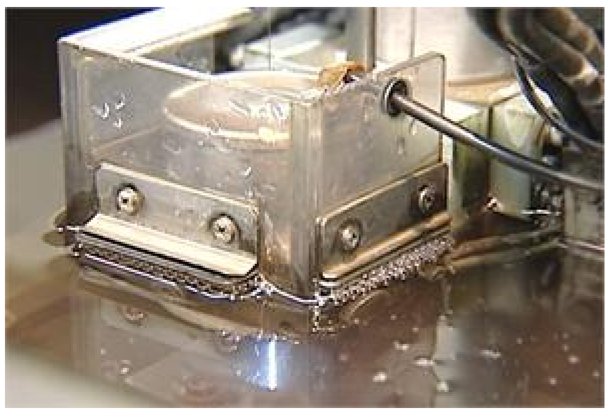
Electrical discharge machining (EDM) is a group of nontraditional, automated machining processes that shape **electrically conductive** materials, including **carbides**, **polycrystalline diamond**, and even hardened steels. **Conventional EDM**, or **ram EDM**, is the most common EDM process and is popular in mold and die tooling.

In conventional EDM, manufacturers position a customized electrode over the top of a **workpiece**, leaving a small gap between the two components. Submerging this setup in **dielectric liquid** helps to ensure the electrode and workpiece remain separate from one another. Manufacturers then send an electrical **current** through the electrode. As the current passes through the gap separating the electrode and workpiece, it creates an electric arc, which vaporizes unwanted particles of material from the workpiece. The dielectric liquid also helps focus the arc to a localized area, acts as a **coolant**, and flushes away the unwanted material pieces.

Conventional EDM can quickly produce complex parts with accurate tolerances and edges free of **burrs**. Since conventional EDM does not generate **cutting forces**, it is able to produce small and fragile parts with intricate details and superior finishes.

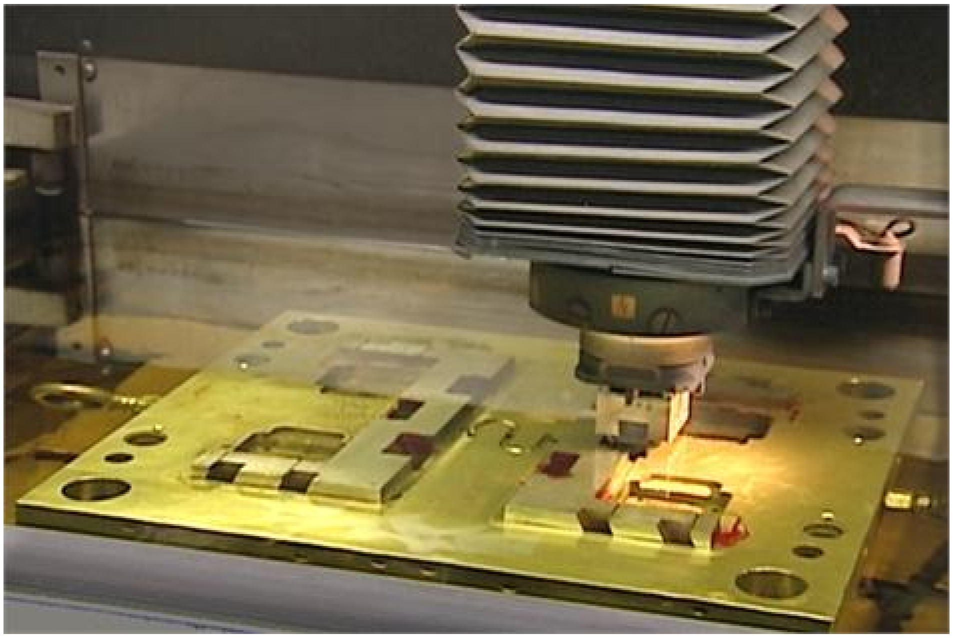


Automated EDM machines submerge an electrode and workpiece in dielectric fluid.



EDM produces an electric arc between an electrode and workpiece.

The benefits provided by the **EDM** process are often negated by the exceedingly high costs and long lead times associated with electrode production. To minimize these disadvantages, manufacturers have started applying AM as a secondary process within EDM.



AM processes can be used to create one electrode that possesses the features of several simpler electrodes.

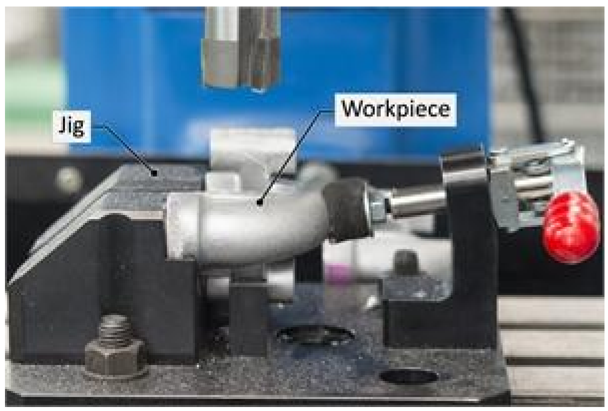
EDM electrodes are made from **graphite** or **copper**, soft materials that quickly lose their shape due to **wear**. As a result, each EDM process requires the use of multiple electrodes. The number of electrodes required per operation increases as part design becomes more complex and a part requires multiple cavities. Due to the ease with which AM processes are able to build complex parts, manufacturers have been able to create a single electrode that combines all the features required to make multiple cavities at one time. This has dramatically cut costs as well as the lead times associated with electrode production.

Manufacturers have also begun researching the potential benefits to building EDM electrodes out of more advanced AM materials. For example, replacing graphite and copper electrodes with electrodes made from a material that has greater **wear resistance** may provide further reductions to costs and lead times.

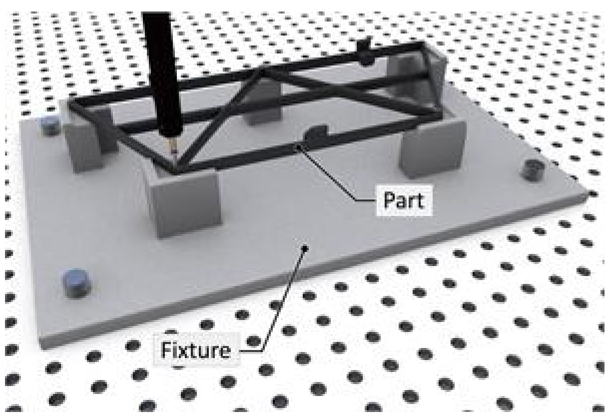
Manufacturers can also apply AM methods to build customized **workholding devices** that align, assemble, and clamp a workpiece or machine components during **drilling**, **welding**, or other processes. For example, a **fixture** positions and holds a workpiece during a manufacturing process, while a **jig** not only positions and holds a workpiece but also locates a **machine tool** and guides its movements. Unlike other workholding devices, such as **clamps** and **vises**, jigs and fixtures are designed to address workholding requirements that are unique to one specific process or part design.

Using traditional machining processes to make a jig or fixture is both costly and time consuming, especially if a device requires several production cycles to achieve and verify its performance. Machining also often limits device designs because complex geometries, such as **interlocking** components, incur additional expense.

Manufacturers can eliminate many of the limitations by additively manufacturing jigs and fixtures. For example, the ease with which AM processes build complex parts allows for greater design freedom and highly customized devices that better meet process and part requirements. Since AM methods can also build such complex parts more quickly than machining processes, manufacturers reduce their time spent **proving** part-design capabilities, which minimizes lead times and reduces costs.



Jigs and fixtures are customized to hold uniquely shaped parts.



AM processes can create customized workholding devices, like jigs and fixtures.

241: Nondestructive Testing for Additive Manufacturing

Additive manufacturing (AM) creates complex final parts by joining materials together, usually layer-by-layer. Like all manufactured parts, AM parts require inspection to confirm they meet **standards** and are free of **defects**. Defects are severe flaws, or **discontinuities**, that exceed a part's **specifications**. Defects affect part reliability and performance and can even result in **catastrophic failure**, so inspection helps guarantee a part's safe operation.

Destructive Testing

Destructive testing includes a number of inspection processes that take random sample parts from a **production batch** and test them using methods that break or otherwise scrap the parts. For example, destructive testing may involve cutting an AM part into cross-sections in order to see and inspect the quality of the part's interior. As a result, destructive testing renders a part unusable afterwards.

Nondestructive Testing, courtesy of Ukrphoto

Nondestructive testing (NDT), on the other hand, includes any inspection process that evaluates a part without permanently damaging it. For example, some nondestructive testing processes create an accurate image of a part's interior, allowing inspection personnel to look for defects without cutting the part open. Therefore, unlike destructive testing, nondestructive testing does not affect a part's future usability.

A wide variety of nondestructive testing methods, ranging from very basic to more advanced techniques, are currently in use across manufacturing. Several of these methods are appropriate for use in **AM** part inspection, and some methods are more commonly utilized than others. **NDT** provides several AM manufacturers with several advantages, but it is not without challenges as well.

Additive manufacturing is often ideal for creating highly customized parts during **small-batch runs**. As a result, using NDT for AM part inspection is often far more practical than destructive testing methods that would scrap one or more of the already limited number of AM parts produced. Furthermore, since NDT does not affect the usability of parts, it can inspect every AM part produced, increasing confidence in overall AM part quality and reliability.

Manufacturers can also utilize NDT during almost any stage of an AM process. For example, manufacturers can use NDT to assess build material quality prior to starting an AM process. AM part quality often depends on manufacturers using high-quality build material with very specific properties and characteristics. Using NDT to verify that build materials meet the required specifications prevents a significant amount of waste and loss of valuable production time. Furthermore, many AM manufacturers also use NDT to monitor the quality of each individual part layer during the AM build process. This allows manufacturers to identify when defects are forming and sometimes adjust parameters during the build process to fix the defects. Finally, manufacturers can also verify the quality of a finished AM part or the continued integrity of an in-service AM part using NDT methods. Overall, NDT can help reduce the amount of AM parts rejected, **rework** time spent, machine downtime, and any associated costs.

Properly establishing NDT, however, can be costly because manufacturers usually must purchase specialized equipment and **consumables**. Since detecting every type of discontinuity in every type of part often requires using more than one NDT method, manufacturers must also invest in two or more NDT methods. Additionally, most NDT methods require intense operator involvement, which increases the chance of human error or fraud. Ensuring accurate and valid test results requires manufacturers also invest in training NDT technicians so they are highly skilled and meet minimum **certification** levels.

Furthermore, many of the standard AM part characteristics and features present some significant challenges to using NDT. For example, AM parts have usually highly complex shapes and geometries since AM processes can integrate multiple components, intricate **internal channels**, and **lattice structures** into a single part build. Such complex external and internal part geometries can limit access to part surfaces and, thus, limit what some NDT methods are able to inspect. Additionally, the AM layering process results in parts with rough external and internal surfaces, which limits what NDT methods are appropriate to use and can make it challenging for technicians to correctly interpret some test results.

Finally, compared to long-established traditional manufacturing processes, like **machining**, **casting**, and **forging**, additive manufacturing is a relatively new and highly dynamic field. AM methods and applications are constantly evolving as manufacturers develop new build materials and processes. Additionally, using AM processes to create functional **end-use** parts is still a relatively new development. As a result, it is difficult to know which flaws are critical defects in an end-use AM part. While most NDT methods that were originally used to inspect cast or forged parts have been successful in inspecting AM parts, the guidelines, specifications, and **physical reference standards** for these methods have not yet been tailored specifically to AM part inspection.

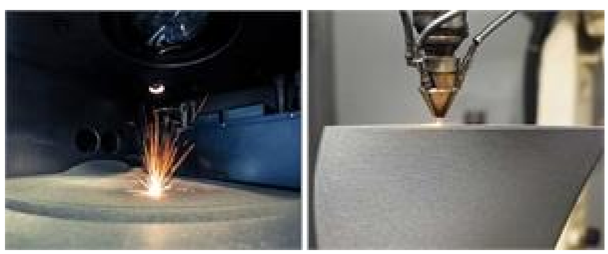
Additive manufacturing encompasses a variety of different technologies. While manufacturers can categorize AM technologies in a variety of ways, most group them according to the method they use to create part layers. Currently, manufacturers recognize seven distinct additive manufacturing methods:

- **Material extrusion** creates part layers by depositing heated build material onto a **build platform** that moves downward with each layer. Material extrusion processes most commonly create parts out of **thermoplastic** materials, but some can use **composite** and **ceramic** materials.
- **Vat photopolymerization** creates part layers by selectively curing areas of liquid **photopolymer** with **ultraviolet light** (UV light). Vat photopolymerization processes primarily create plastic parts.
- **Material jetting** creates part layers by selectively depositing droplets of build material onto a build platform. Material jetting processes generally creates parts from **thermoset** plastics or wax.
- **Binder jetting** creates part layers by selectively depositing a liquid **binder** onto a thin layer of powdered build material. Binder jetting processes create parts from various metals, plastics, ceramics, and composites.
- **Powder bed fusion** (PBF) creates part layers by selectively fusing or melting powdered build materials with a **laser** or **electron beam**. Powder bed fusion processes most frequently create metal parts, but they can also create plastic, ceramic, and composite parts.
- **Directed energy deposition** (DED) creates part layers by melting build materials as they are fed into a laser or electron beam and onto a base. Directed energy deposition processes create parts out of metal powder or wire.
- **Sheet lamination** builds part layers by binding together thin sheets of build material. Most sheet lamination processes use paper as build material, but **ultrasonic consolidation** (UC) is a specialized sheet lamination process that uses thin metal sheets.

Since each AM method differs in the way it creates a part and the material it uses, each method can result in different discontinuities and defects. As a result, each AM method produces parts that often require inspection using different NDT methods.

Material Extrusion and Vat Photopolymerization

Material Jetting and Binder Jetting



Powder Bed Fusion and Directed Energy Deposition

Visual testing (VT) is often the first NDT method manufacturers use to evaluate a part's surface condition and determine whether any discontinuities and defects are present.

At its simplest, VT involves a certified technician closely examining a part using no equipment. Adequate lighting is critical to ensuring the effectiveness of visual testing, so most specifications require a minimum **illuminance** level of artificial light. Additionally, parts must be free of dirt and coatings, which can hide surface discontinuities from sight.

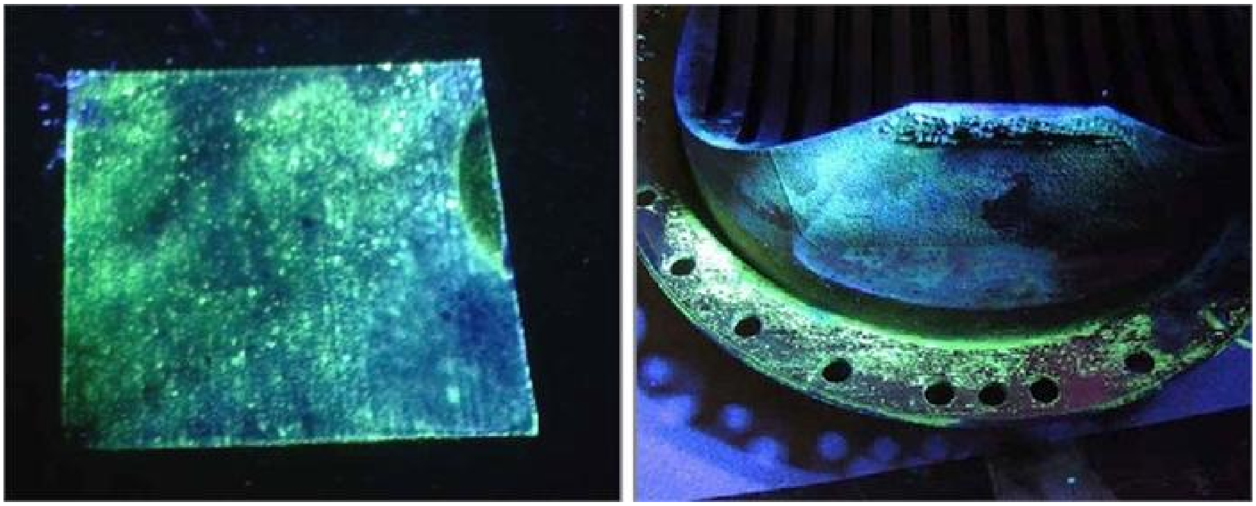
Visual testing is a relatively simple and economical NDT method than can be used to inspect final AM parts or monitor AM build processes. Properly trained and certified NDT technicians can locate and identify most surface-breaking discontinuities on AM parts of virtually any size and material, including those with post-build surface roughness. Technicians may need to use **optical instruments** in order to detect discontinuities smaller than 0.25 in. (6.35 mm). These instruments range from simple **magnifying lenses** and **microscopes** to more advanced **video borescopes** and **vision systems**.

VT, however, cannot find any **subsurface**, internal part discontinuities. Its **repeatability** and effectiveness can vary and often depends on the technician's expertise and the testing environment. Working conditions can significantly affect a technician's ability to focus and concentrate, which is critical to ensuring visual testing accuracy.

Unaided Visual Inspection of AM Part, courtesy of TWI Ltd.

Aided Visual Inspection

Liquid penetrant testing (LPT) is a relatively simple and straightforward NDT method. It is a multi-step process that uses a **penetrant**, or liquid dye. Manufacturers sometimes use LPT to locate surface discontinuities that may not be detectable during visible testing.



Excessive indications on AM parts with rough surface finishes. Courtesy of Mazurek, M. & Austin, R., *DIASC Journal*.

During LPT, a technician coats a part surface with penetrant. The penetrant must remain undisturbed on the part surface for a specified length of time, or **dwell time**, so it can flow into any surface discontinuities. After the dwell time, the technician removes excess penetrant from the part surface before applying a **developer**. The developer is usually an **absorbent** fine white powder that draws the penetrant out of any discontinuities to form clear visible **indications**. **Color-contrast** penetrants create indications that are easily visible under ordinary light, but **fluorescent** penetrants create indications that are only viewable under **UV light**.

Liquid penetrant testing is typically an economic NDT method, especially when compared to more advanced NDT methods that may require expensive equipment and consumables. While it cannot detect subsurface flaws, it can detect exceedingly small surface discontinuities. Performing LPT on rough or **porous** surfaces, however, results in excessive and inaccurate indications. Due to the characteristic rough **surface finish** and porosity of many AM parts, they require extensive machining and **polishing** before liquid penetrant testing can be utilized. These additional **post-processing** steps can add to overall production time and costs, making LPT less economical and practical in the long run.

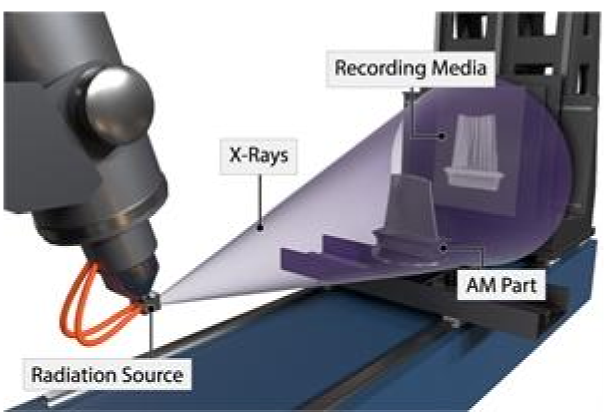
Eddy current testing (ECT) is a common NDT method that uses **electromagnetic induction** to inspect **conductive** metal parts.

During ECT, **alternating current** (AC) passes through a conductive coil, producing a magnetic field that expands and collapses as the AC reverses directions. When a technician places the coil near a metal part, the coil's magnetic field generates, or induces, circular **eddy currents** within the part. The eddy currents produce a secondary magnetic field that results in a disturbance, or **impedance**, to the coil's AC flow, which can be measured using a **voltmeter** or **ammeter**. Any discontinuities in the part that occur perpendicular to the eddy current flow will reduce the strength of the secondary magnetic field and change the amount of impedance detected. Eddy current testing is very sensitive and can detect very small surface and subsurface discontinuities. However, a part's surface finish can interfere with test sensitivity, so AM parts often require post-processing to smooth rough surfaces prior to performing ECT.

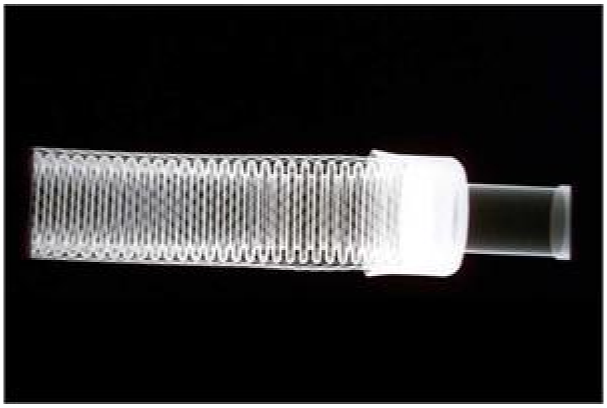
Radiographic testing (RT) is a relatively advanced NDT method that can detect internal part discontinuities.

During RT, a **radiation source** directs **x-rays** or **gamma rays** toward a part. X-rays and gamma rays are types of **electromagnetic radiation** that can penetrate into and pass through virtually any material. The part absorbs some of the radiation as the rays pass through it. The amount of radiation that a part absorbs depends on its **density** and thickness. Areas of porosity or other internal discontinuities absorb less radiation than areas that are fully dense and free of flaws. The remaining, unabsorbed x- or gamma rays exit the other side of the part, where they contact **recording media**, typically either film or a **fluoroscopic screen**. The recording media absorbs the remaining radiation, which creates a two-dimensional (2D) image, or **radiograph**, of the part's interior. Part discontinuities appear as darker areas in the radiograph.

Unlike some other NDT methods, radiographic testing can inspect virtually any part, regardless of material type. It is also highly accurate and repeatable. However, RT effectiveness decreases as AM part complexity increases due to the difficulty in imaging parts with areas of varying thickness, and it is not always able to reliably locate cracks. Cracks must occur parallel with the rays to appear on the radiograph. Several process variables, such as the type and amount of radiation and the amount of time an AM part is exposed to the radiation, also affect the radiograph's quality. RT technicians require extensive training to ensure they correctly perform the test, follow specific safety procedures, and wear appropriate **personal protective equipment** (PPE) due to the significant health hazards posed by radiation exposure.



Radiographic Testing



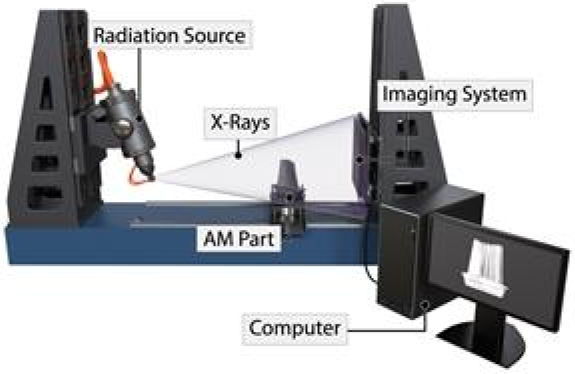
Radiograph of AM Part, courtesy of NASA White Sands Test Facility

X-ray computed tomography (x-ray CT), or **micro computed tomography** (microCT), is an advanced type of radiographic testing that is currently the most widely used NDT method for AM part inspection.

As with conventional radiographic testing, x-ray CT exposes a part to x-rays and creates an image of the part's interior by recording the amount of radiation that exits the part. However, instead of creating just one 2D image of a part's interior, x-ray CT rotates the part to create multiple images of a part at many different angles and locations. A digital **imaging system** connected to a computer records and collects these images. Specialized computer **software** then reconstructs the images into a high-**resolution** three-dimensional (3D) image of the part's interior that shows whether an AM part has any internal discontinuities.

Like conventional RT, x-ray computed tomography can inspect AM parts made from any material with a high level of accuracy and repeatability. Unlike RT and other NDT methods, x-ray CT creates a complete, detailed image of a part's exterior and interior, allowing for thorough part inspection. Comparing the 3D image to the original 3D part model also allows AM manufacturers and designers to identify and address any discontinuities and variations from the expected design. Additionally, due to the many different image angles, CT is often able to detect discontinuities located deep within part layers better than conventional radiographic testing, and it is less affected by increasingly complex parts with varying thicknesses.

However, x-ray CT is still only able to reliably locate cracks that are parallel with x-rays. The process is also significantly slower than RT due to the amount of **processing time** necessary for the computer to compile all the 2D images into a 3D image. Additionally, the costs associated with implementing x-ray CT are much higher than conventional radiographic testing, which is already quite expensive. Finally, as with radiographic technicians, x-ray CT technicians also must follow specific safety procedures and wear appropriate **PPE** due to the added risk of radiation exposure.



X-Ray Computed Tomography

CT Scan of AM Part with Defects

Ultrasonic testing (UT) is a common NDT method that uses high-**frequency sound waves** to locate **microscopic** surface and internal discontinuities in parts.

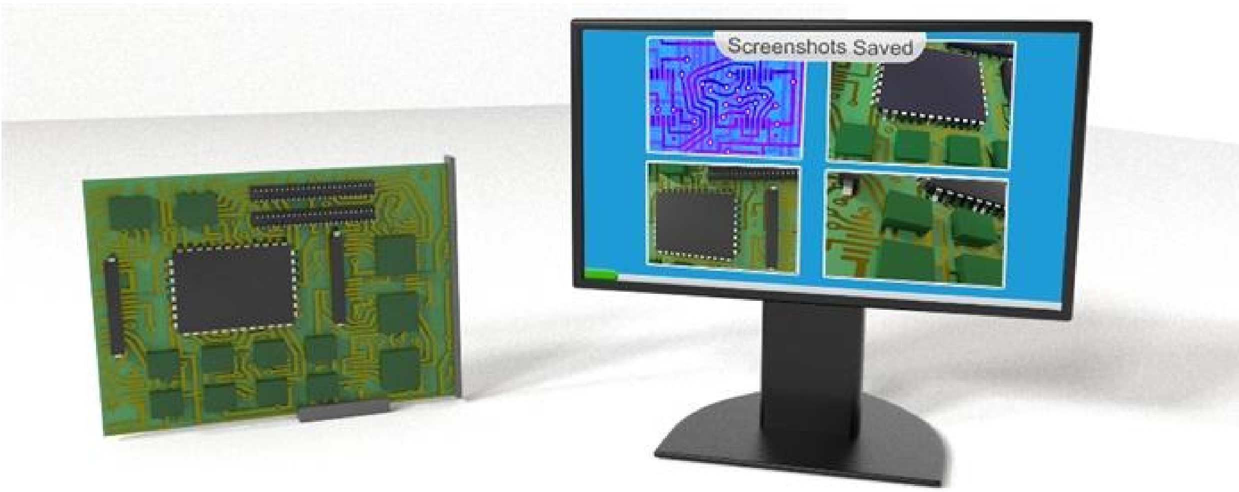
During UT, a technician places a **transducer** on a part surface that has been coated with **couplant**. A transducer is a probe-like device that converts electric **voltage** into sound waves, while the couplant is a gel-like substance that helps transfer the sound waves from the transducer into the part. Inside the part, a sound wave travels until it hits a discontinuity. A discontinuity will **reflect** the sound wave and cause it to travel back toward the transducer. The transducer detects the reflected sound wave, or echo, and converts it back into voltage. A **flaw detector** connected to the transducer displays the voltage as **amplitude** signals that the technician uses to determine the discontinuity's location, size, and shape.

Ultrasonic testing is highly sensitive and can detect discontinuities that many other common NDT methods may miss. It is appropriate for use on AM parts made from all types of build materials. However, it requires a certified technician with extensive training to correctly choose the process variables, operate the equipment, and interpret test results. Excessive surface roughness can make test results challenging to interpret, while irregularly shaped, very small, or exceptionally thin AM parts can be difficult to inspect. UT usually requires the transducer contact the part surface, which is not always possible with the reduced number of inspection surfaces available due to AM part integration.

Ultrasonic Testing

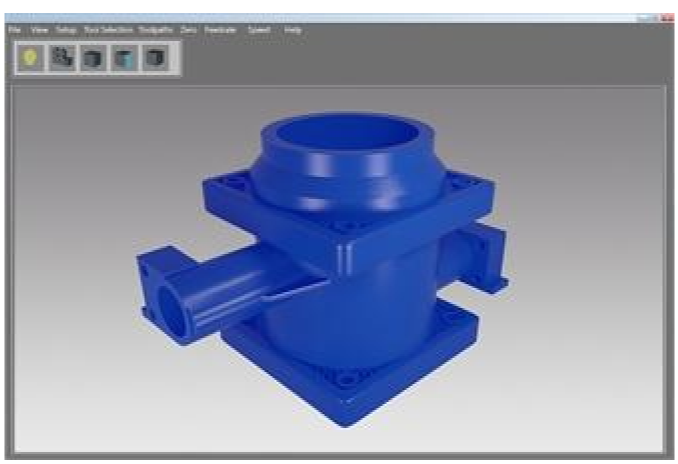
AM part integration reduces the inspection surfaces available to ultrasonic testing.

242: Reverse Engineering for Additive Manufacturing



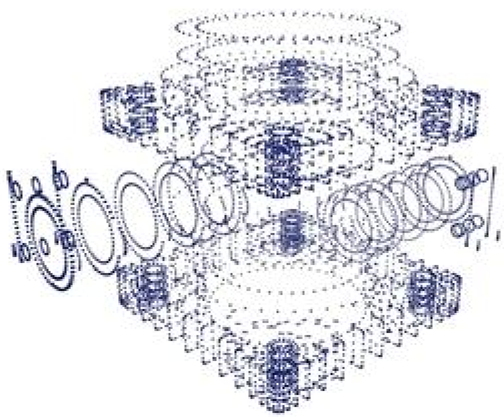
Engineering is the field of designing and creating machines, electronics, buildings, parts, and structures. For example, engineering creates both roads and the vehicles that travel them. **Reverse engineering** (RE), in contrast, is the process of determining the design and creation of an existing object. Reverse engineering, also known as **back engineering**, has a variety of purposes and is used in multiple industries. Computer hardware manufacturers, for example, often reverse-engineer **microchips** by disassembling them and saving photographs of each layer. These photos form a record of the chip components and how they are assembled, which engineers can then refer to if needed. Similarly, mechanical engineers can use RE to determine how a vintage car or truck engine was manufactured. Part designers often use digital scanning tools and **computer-aided design** (CAD) software to reverse-engineer and recreate existing parts. These RE processes may be used to keep a library of part designs, create a replica of a rare or vintage part, or analyze a part to improve on the next version.

Additive manufacturing (AM) utilizes **RE** for various purposes, but the basic process is the same across different applications.



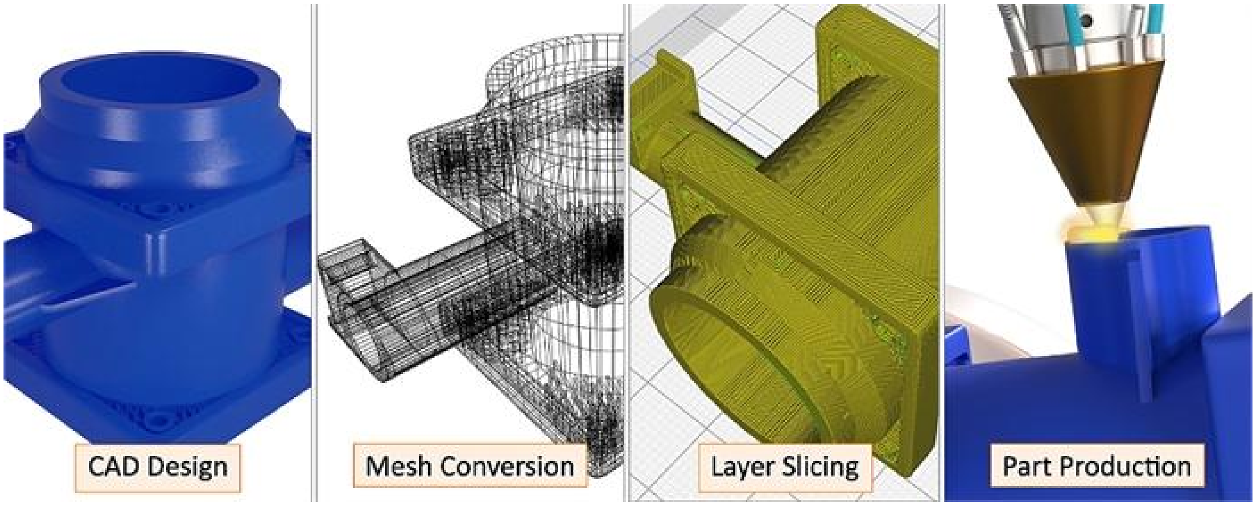
CAD Model

The AM design and engineering process generally consists of designing a part, creating a digital model of the part in **CAD** software, and converting the CAD file into usable machine instructions so the AM machine can build the part. Consequently, reverse engineering a part in order to recreate it using AM requires the creation of a precise digital CAD model, generally through scanning the part.



Point Cloud

Scanning tools, such as **3D laser light scanners**, can record the geometry, or shape, of a part and replicate it as a digital **point cloud**. A point cloud is a grouping of virtual dots that represent locations on a part's surface. Connecting these dots forms a digital image of the part's surface called a **mesh**. A mesh is similar to a point cloud, but it connects points to form an image using interconnected shapes. Engineers can then convert the mesh to a CAD model in order to build the part with an additive process.



Like any part production process, **AM** begins with part design. An engineer or part designer generally begins by creating a **three-dimensional** (3D) virtual model in CAD software. CAD software allows designers to not only see what a part will look like, but to simulate how it will react to various conditions and uses. The CAD model must then be converted to an **STL** or **AMF** file. STL is a type of mesh software that uses interconnected triangles to represent the part surface. AMF is a newer format that functions similarly but also provides more advanced **data**, such a colors. Since AM processes deposit or fuse material in layers, it is generally then necessary to use a **slicer** software to divide the model into the layers that the AM machine will deposit. An engineer or specialized software then creates a **G code** program or a machine-specific **build file** to direct the movements of the AM machine during the part production process. Reverse engineering begins with scanning a physical part in order to create a virtual model of the part. Once the part exists as a digital model, engineers can begin the AM part design and production process.

Reverse engineering a part and rebuilding it with AM can be used for a number of applications. RE can replicate parts that are no longer manufactured or quickly produce an item that would otherwise take too long to create or cost too much to ship.

RE with AM can be incredibly helpful in areas that are far from cities or manufacturing facilities. Employees on remote worksites, including military personnel, can reverse-engineer parts to repair or maintain equipment. Using RE and AM in the field often takes much less time and costs less than shipping the part.

Similarly, medical personnel in areas with limited access to supplies can also benefit from reverse engineering and AM. RE with AM can replicate medical equipment and devices such as **respirators** or even **prosthetics**. In response to the COVID-19 pandemic, some manufacturers used RE and AM to respond to critical shortages and create respirators for healthcare workers. Engineers have even used RE to additively manufacture a prosthetic elbow joint that functions almost identically to a biological human elbow.

RE can also help to preserve and restore historic and cultural structures. If, for example, a historic building has crumbling concrete decorations, engineers can scan them to create a point cloud. If the decoration has broken or missing areas, the point cloud will record them. Once the point cloud is converted to a CAD file, engineers can manipulate the **3D** model to fill in any missing or flawed areas. They can also use **binder jetting**, **material extrusion**, or another process to rebuild the concrete item.

In addition, RE can be useful when designing new products. Reverse engineering a newly designed part or **prototype** can help designers to find flaws or issues that they may have overlooked during the design process. Similarly, reverse engineering an existing part can help designers improve upon its design and increase the quality of future products.

Unfortunately, there are also illegal uses for reverse engineering. In the United States and some other countries, part and product designs are considered **proprietary** to the company that created them. This means that companies own their part designs, and it is theft to use their design without permission. If someone reverse engineers a proprietary product and recreates it, the person can face criminal penalties.

Manufacturers use multiple methods to scan parts for reverse engineering.

Photogrammetry utilizes photography to create images of an object from multiple angles. Rather than creating a point cloud or mesh, photogrammetry software uses photos as data to construct a 3D model of an object. It generally requires at least 100 photos for the software to construct an accurate model of an object's geometry. Since photogrammetry requires only cameras and photogrammetry software, the initial cost is lower than other RE scanning methods. It is also an effective way to scan large objects or areas. Engineers can attach cameras to a drone, which can fly over tall buildings or other large objects to scan areas that would otherwise be impossible to reach. However, photogrammetry is much less accurate than other methods.

Computed tomography (CT) scanning is another method used in reverse engineering with AM. CT scanning is similar to the CAT scans used in the medical field. It uses **X-rays**, which create an image of an object's interior by recording the amount of **radiation** that passes through it. Instead of creating just one image, CT scanning rotates the item to create multiple images from many different angles and locations. A digital **imaging system** connected to a computer records and collects these images. Similar to photogrammetry, specialized computer software then reconstructs the images into a 3D model of the object. However, CT scanning is far more precise and accurate than photogrammetry since it scans the part's internal structure.

Engineers can also use a **coordinate measuring machine** (CMM) to capture an object's geometry. CMMs are **metrology** tools that work by physically contacting multiple points of a part or item with a sensitive **stylus**. Traditional CMMs can be used only on objects small enough to fit within the machine's rigid frame. However, portable CMMs such as **CMM arms** are now available for objects that are larger or cannot be moved. A CMM creates a point cloud based on the data it collects, so it is crucial to use enough points of contact to create an accurate digital model.

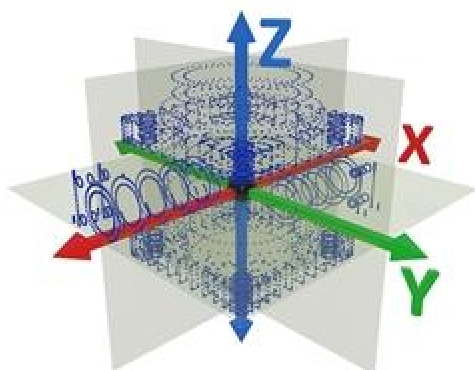
Laser scanning is a type of **3D optical scanning** that is also used in RE and metrology. Laser scanners are generally portable or hand-held devices that project a **laser** onto an object while a camera captures its reflection. Lasers are highly concentrated beams of light that bend or distort when they meet a surface. The amount and direction of distortion indicates a part's shape and location in physical space. Software then compiles the laser reflection data into a 3D model of the object. Laser scanners can use one or more lasers to detect different geometries, and they are very accurate and precise. Laser scanners can also be mounted on CMMs for noncontact scanning.

Structured-light scanning, like laser scanning, is a type of 3D optical scanning. Rather than a laser, structured light scanners project a pattern of light onto an object. A camera captures the distortion of the light pattern as it contacts the object, and software compiles the reflection data into a digital 3D model. Structured light scanners are mounted rather than hand-held, which increases their accuracy, and they can also cover more area of an object with each scan than a laser scanner.

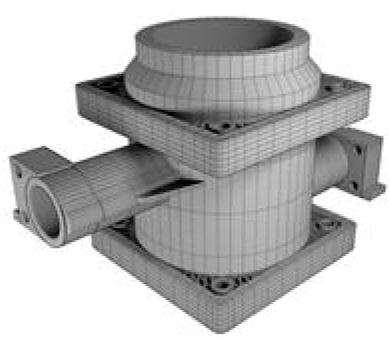
Each point in a point cloud represents a location in physical space. The point locations are defined using the **Cartesian coordinate system**, which consists of three straight lines, or **axes**. In the Cartesian coordinate system, the X axis is **horizontal** in a left-to-right direction, the Y axis is horizontal in a front-to-back direction, and the Z axis is **vertical**. The point where all three axes meet is called the **origin**. Any point in physical space can be located and defined by its position relative to the axes and origin.

Once an engineer has scanned their object and created a point cloud, they use **point cloud modeling software** to convert it into a mesh. A mesh essentially connects the points in a point cloud with lines. This creates a number of connected **two-dimensional** (2D) shapes called **polygons**, which give the appearance of a mesh or net.

An important function of point cloud modeling software is cleaning up the point cloud. Since laser and structured-light scanners are such precise, sensitive instruments, even small variations, flaws, dirt, or particles on an object's surface can add points to the cloud. These stray points are known as **noise**, or **scatter**. Noise can distort the mesh and cause it to be less accurate, so it should be removed. In addition to cleaning and converting the cloud, engineers can also use point cloud modeling software to modify the mesh to fill in broken areas of a scanned part or make other adjustments. The mesh can then be imported into CAD software to create the final model.



Cartesian Coordinate System



Mesh

A manufacturer that creates **molds** and molded parts is incorporating additive manufacturing into their workflows. They want to shift from traditional, straight **cooling channels** to far more effective **conformal cooling** channels. In order to achieve conformal cooling, they plan to reverse engineer existing molds and modify the cooling channels.

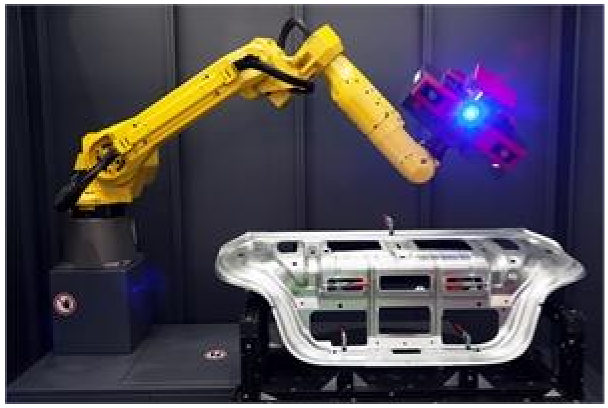
First, an engineer uses a laser scanner to scan the mold and create a point cloud. It is important that the mold is clean and free of debris to reduce noise in the point cloud. Once the scan is complete, the engineer cleans up the point cloud in point cloud modeling software, then converts it to a mesh. They then import the mesh into CAD to create a solid 3D model. In this software, they can adjust the cooling channels from straight to conformal by bending them more closely around the mold cavity.

Once the CAD model is complete, the engineer can convert it to an STL file, then use slicer software to digitally slice the model into the layers that the AM build will create. The engineer then creates a G code program or another type of build file to direct the machine's movements as it builds the mold. Finally, an AM machine, such as a **powder bed fusion** (PBF) or **ultrasonic consolidation** machine, can build the part to **near-net shape**.

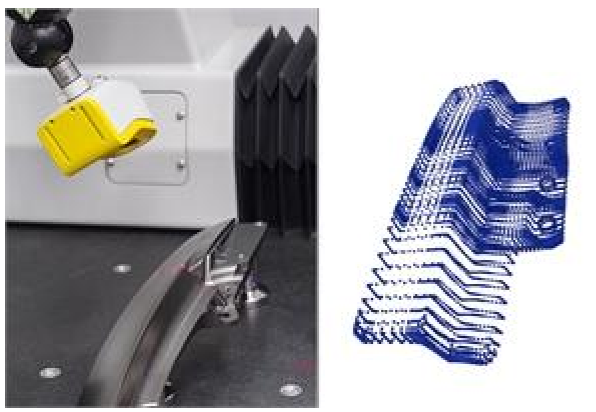
Even if a manufacturing facility does not need to use RE to create new or replacement parts, it can still be useful for other purposes. If a designer or engineer creates functional prototypes to test a newly designed part, for instance, reverse engineering the part can reveal design issues or potential improvements. For example, after scanning a part, the point cloud may include uneven points that indicate an AM part has printed incorrectly. The designer can then adjust the design file to correct this issue. Alternatively, the point cloud or mesh could indicate a somewhat uneven surface that should be rectified with **post-processing**, such as sanding or **plating**.

Similarly, RE can also help manufacturers create improved versions of existing products. Scanning and reverse engineering an existing part can provide designers and engineers a realistic view of the part instead of the original, idealized design file. They can then use the new mesh and CAD files to create a new, improved design. This process can be especially helpful when a manufacturer is first beginning to adopt additive manufacturing. RE is an effective way to import existing part designs and update them for AM processes. AM has greater design flexibility than traditional manufacturing processes, so a shift to AM generally allows designers to improve or enhance a part’s features.

A manufacturer may also use RE to maintain an updated inventory of part designs. Scanning existing parts to create a library of CAD files is an effective way to keep records of existing or legacy parts for future reference.

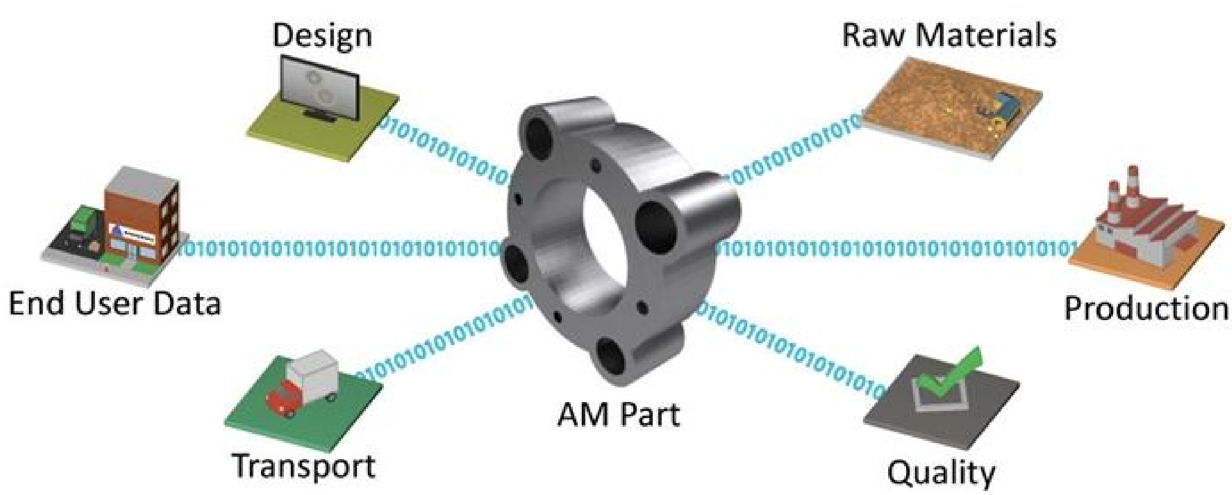


CAD models can begin as part scans.



Point clouds from scans can reveal design defects.

251: The Additive Manufacturing supply chain

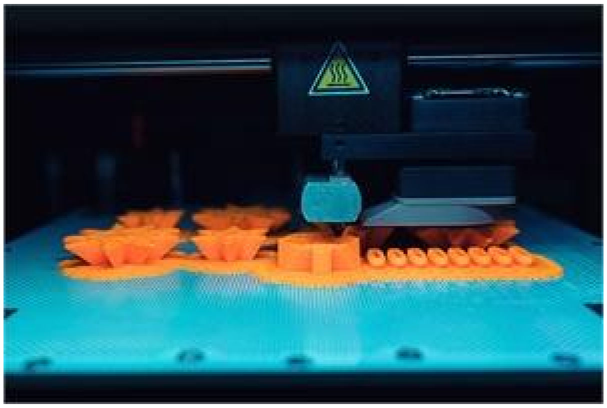


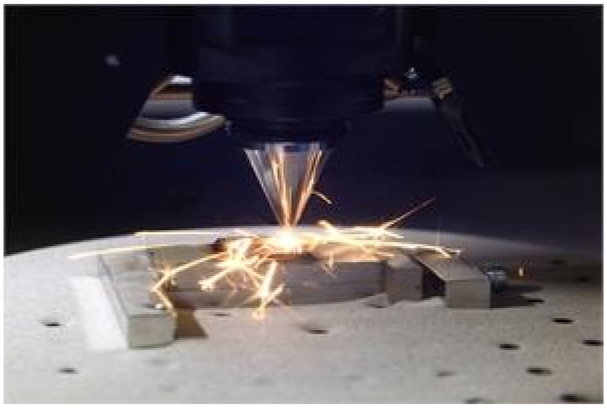
Every product that reaches a customer is the result of a complex series of exchanges between many different businesses or facilities. For example, one business might supply the raw materials necessary to make a product, and another might create parts from those raw materials. A different business or facility might assemble the parts into a finished product and send them to yet another business that stores and distributes the finished product. Finally, a different business might sell the product to customers. These companies that exchange information, goods, and services in order to create and sell a specific product form a **supply chain**. Typical supply chains within manufacturing often consist of raw material suppliers, product designers and engineers, manufacturing facilities, warehouses and distribution centers, shipping companies, and retailers, all of which are scattered throughout the world.

A manufacturer's success often depends on its supply chain providing a continuous flow of materials, products, and information. As a result, **supply chain management** has become a necessary part of manufacturing. Supply chain management involves coordinating a variety of activities, from initial material purchases to final product distribution.

Additive manufacturing (AM) has the potential to revolutionize traditional supply chains and their management. AM technology turns digital **three-dimensional** (3D) models into physical objects by building them up in layers. In additive manufacturing, engineers create a part design and then convert it to a 3D computer model. An AM machine turns the computer model into a finished part by stacking and joining layers of material. **End-use** AM parts often have improved complexity and functionality compared to traditionally manufactured parts. AM may introduce several advantages to supply chain management, possibly including waste reduction, the combination of production and assembly into fewer steps, minimized storage needs, and increasing responsiveness to customers.

Though adopting AM in a facility may have a high up-front cost, supply chain managers must consider the affects AM may have on their supply chain as well as the **total cost of ownership** (TCO) of new programs and devices. TCO is the purchase price of an asset plus the costs of operation. If using AM processes allows a manufacturer to produce more products in less time, or to spend less on materials and storage, then the up-front cost will be balanced by reduced daily costs. By evaluating TCO, a supply chain manager can decide if additive manufacturing programs will prove to be efficient investments over time.





Compared to traditional manufacturing, **AM** allows companies to reduce both the amount of materials required to create a part and the costs associated with shipping and receiving raw materials.

Traditional machining processes are **subtractive**. In other words, they create parts by removing small chips from pieces of material. Removed chips are generally **waste**, usually unable to be used in further processes. Additionally, most traditional manufacturing processes must use more material to create products with increased design complexity because part complexity is restricted by the shape of the raw material or a tool's ability to reach certain workpiece areas. As a result, creating parts with greater complexity can create increased waste and sometimes be prohibitively expensive.

By contrast, AM processes build parts by joining together layers of material, so there is little to no waste. Some AM parts require **support structures**, which are waste, though manufacturers can generally recycle any excess build material for use in another AM process.

AM technology can also generally create parts with complex features more easily and efficiently than traditional manufacturing techniques. For example, additive manufacturing may require less **assembly**, as certain components can be built up together layer by layer rather than joined together after the fact. With AM, a more complex design does not necessarily require more material.

Because of its potential to reduce waste without sacrificing complexity, additive manufacturing may be useful to companies wishing to adopt **lean manufacturing**. Lean manufacturing is a methodology that focuses on minimizing waste within manufacturing systems while also maximizing productivity.

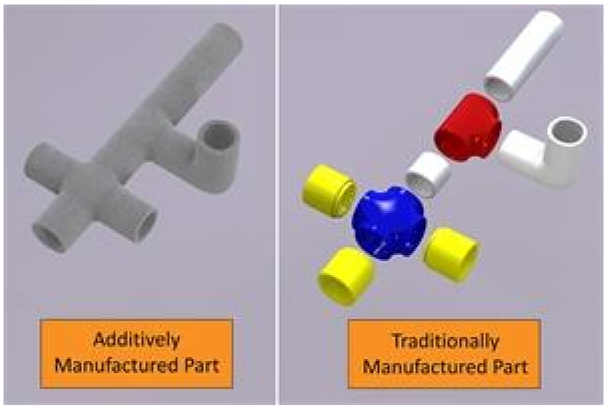
Traditional manufacturing is subtractive.

Material can be reclaimed and recycled in some additive manufacturing processes.

Supply chain management seeks to sustain competitive advantage. Additive manufacturing can provide this for those companies who can differentiate themselves through its use, even when used as a supplement to traditional manufacturing. Two common ways that AM can supplement traditional manufacturing are through customized manufacturing aids and reduced assembly needs.

AM Gripper

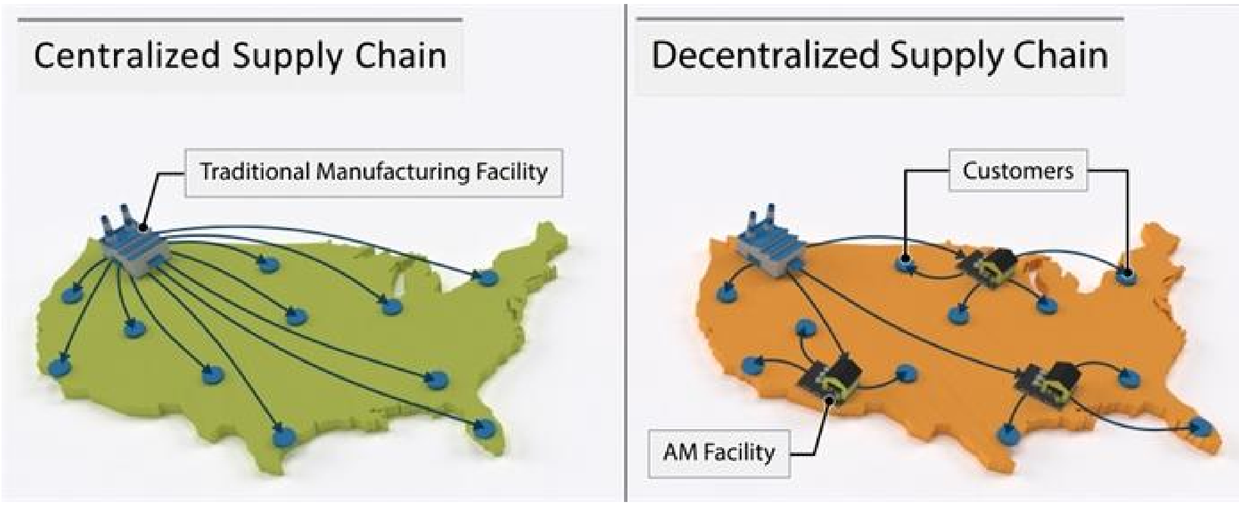
AM can produce complex parts such as **manufacturing aids**, **fixtures**, and tools. These devices can enhance, speed up, perfect, or fix a manufacturing or assembly process. A small AM part may also be added to a traditionally manufactured assembly, such as building an AM **gripper** for a **robotic arm** created through a metal cutting or metal forming operation. These combinations take advantage of AM's ability to create intricate features and traditional manufacturing's ability to rapidly shape large, simple workpieces. Half of all supply chain leaders are using AM to support other manufacturing processes.



Part Integration

The use of AM turns **assembly** into a single-piece system, eliminating assembly costs. Components can be built up together rather than joined together after the fact. This eliminates or greatly reduces the need for the assembly piece of the supply chain.

Supply chains for traditional manufacturing are often centralized, with storage, production, and assembly occurring in one region to reduce shipping times. Distribution then begins from a warehouse in that region. As a result, the bulk of the supply chain may be far from the end customer. Additive manufacturing, however, allows for **decentralization** of elements in the supply chain, which means production can occur much closer to the end customer.



Since additive manufacturing increases manufacturers' ability to produce, assemble, and store parts within one facility, it reduces the need for centralization. As a result, AM processes can meet customers' needs more efficiently through **distributed production** in different locations. For example, rather than one centralized network of facilities shipping products to all customers, some of whom may be hundreds or thousands of miles away, a company can use multiple additive manufacturing facilities in different locations. Producing objects near customers reduces the need for part storage, decreases shipping costs, and greatly reduces **lead time**. Distributed production is flexible enough to respond to unpredictable customer demand without increasing costs for transportation and other logistics.

Another way that AM processes allow for greater **responsiveness** than traditional manufacturing is through quickly replenishing parts. A manufacturer need only change the model file, rather than the whole machine, to create new parts. Because of this, there is no longer a need for **safety stock** or warehouses to store that stock. While manufacturers will still need to store raw materials, doing so generally requires much less space than storing finished goods.

For additive manufacturing, there are many materials to choose from, each with their own characteristics. Important supply chain factors such as cost, printing technology and process, shipping, and storage must be considered to choose the optimal material for a specific project. Supply chain managers must be aware of the advantages of the materials they are sourcing, as well as the unique shipping and storage concerns of each.

For example, some additive manufacturing relies on plastic polymers, such as **nylon**. When polymers are poorly stored, they encounter moisture from the air and later break down during AM processes, resulting in a weakened or defective finished product. Storage that reduces moisture, such as vacuum sealing, will prevent this.

Resin polymers are another common material used in AM. Resin refers to a solid or highly viscous substance of plant or synthetic origin. Due to its high light-sensitivity, resin can be rendered unusable for manufacturing by exposure to UV light. Resin must be kept tightly sealed in dark containers with a small headspace of air to prevent it becoming solid.

Stainless steel, a metal alloy, is used in additive manufacturing in the form of fine powder. If it becomes airborne, this powder represents a health hazard, either from inhaling or absorption through the skin. For many metal powders, fires and explosions are also a real concern for improperly handled materials. For these reasons, manufacturers must use special storage and containment procedures for metal powders, such as **inert transfer**. An inert transfer system, powered by vacuums, prevents the powders from coming into contact with oxygen.

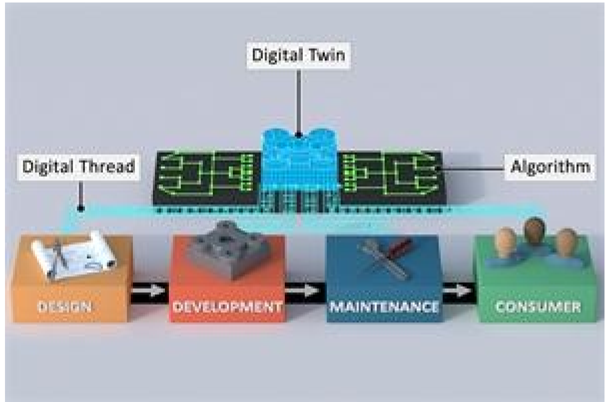
Other materials used in AM include different plastics, titanium, gold, silver, and ceramics. Each material type has unique storage needs that supply chain managers must investigate and plan to adhere to before procuring the material.

Additive manufacturing processes can be time-consuming depending on the part size and design. Manufacturers can optimize AM processes by selecting the best materials for production. Doing so is a crucial earlier step in supply chain management.

Material selection is important not only for part performance, but to make sure production processes and end-use parts are in compliance with applicable laws and regulations. Historically, additive manufacturing was primarily used in **prototyping**, or creating parts to test their design or function. Because prototypes are not used as finished products, early adopters of AM selected materials without much concern for regulations. Today, however, additive manufacturers must ensure **regulatory compliance**. Parts for industries like aerospace, automotive, and medical devices may pose serious safety hazards if they are made incorrectly. A faulty automotive component, for example, can lead to a fatal traffic accident. Regulations for additive manufacturing ensure that parts are made safely.

Material supply compliance can be tracked throughout the supply chain using the **digital thread**. The digital thread is the framework that maintains data on a part or machine to produce a comprehensive view of its movement throughout its **lifecycle**. This framework addresses protocols, security, and standards. Digital threads often work in conjunction with a **digital twin**, which is a **virtual** representation of a physical object.

Additive manufacturing of medical implants requires several levels of regulatory compliance.



The digital thread can track elements throughout the supply chain.

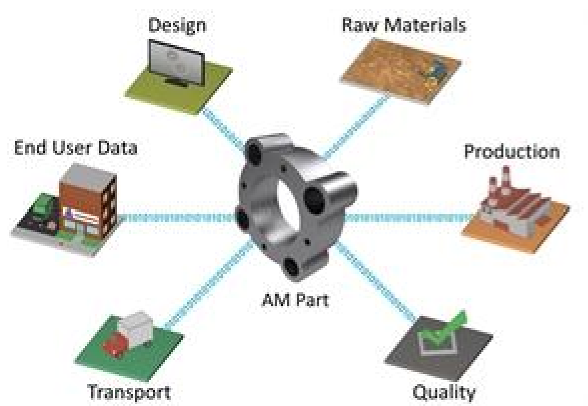
252: Managing the Additive Manufacturing supply chain

Behind every product that reaches a customer, there is an intricate series of exchanges between many different companies. A supplier of raw materials will transfer them to a company that uses them to produce various parts, for example. Then, the parts may travel to a different company that assembles them into a finished product, yet another company that stores the product, and another company that distributes the product to customers. These companies that exchange information, goods, and services with each other in order to create a specific product and make it available to consumers are a **supply chain**. **Supply chain management** involves coordinating and optimizing these various activities, from initial material purchases to inventory production and management to final product distribution.

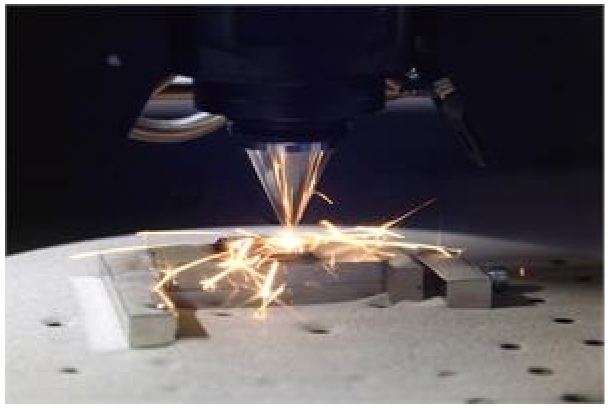
Additive manufacturing (AM) transforms traditional supply chains and their management. AM technology turns digital three-dimensional models into physical objects by building them up in layers. Raw materials used in AM are often in the form of powders or pellets that can be reclaimed and reused if not used in a build. As a result, AM may allow companies to save on material costs. AM may also minimize storage needs and combine production and assembly into fewer steps. The increased responsiveness to customer needs that AM allows can enable greater **agility** in the manufacturing process.

Supply chain managers must consider the affects AM may have on their supply chain as well as the **total cost of ownership** (TCO) of new programs and devices. TCO is the purchase price of an asset plus the costs of operation. By evaluating TCO, a supply chain manager can decide if additive manufacturing programs will prove to be efficient investments over time.

This material is based upon research supported by, or in part by, the U.S. Office of Naval Research under award number N00014-18-1-2881 led by the National Center for Defense Manufacturing and Machining (NCDMM).

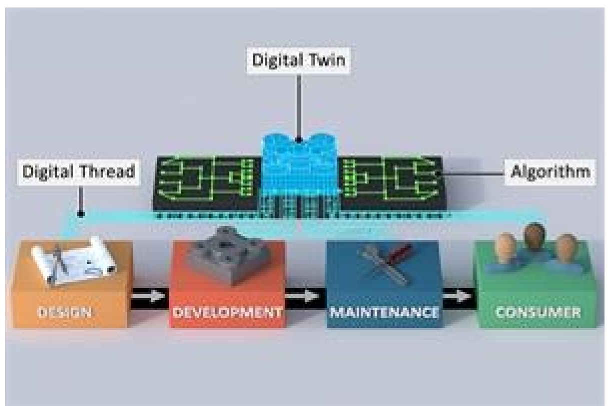


The AM Supply Chain

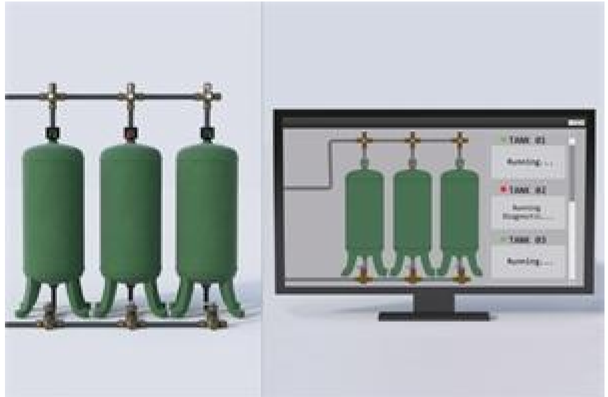


AM with Metal

Supply chain managers may utilize a variety of technologies and methods to follow a part or product throughout its **lifecycle**. One efficient, accurate method is the use of **digital thread**.

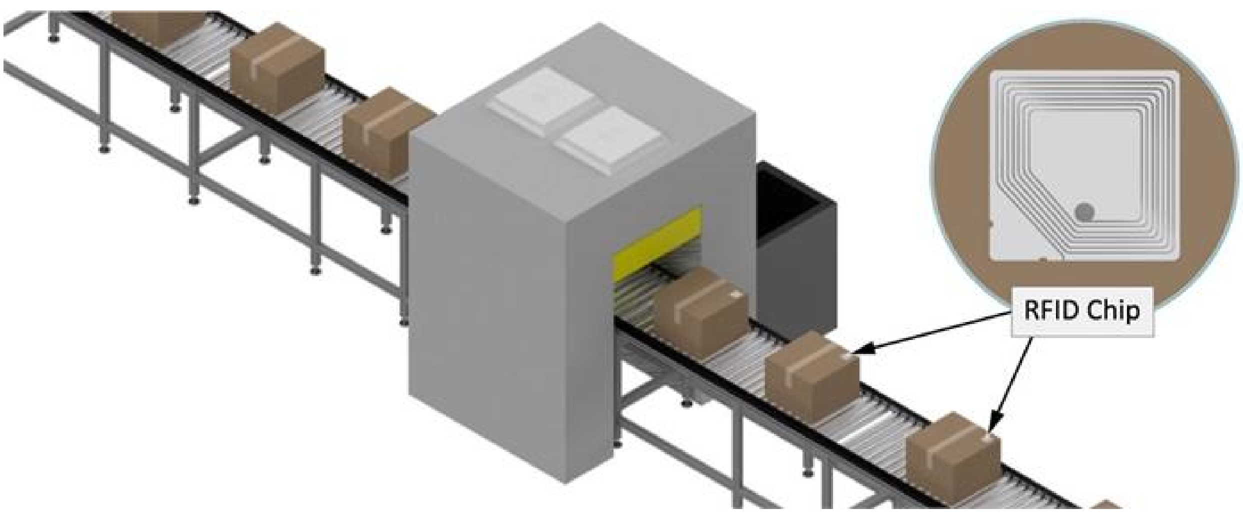


A digital thread is a framework that maintains data on a product from its design to its final use, which produces a comprehensive view of each product's lifecycle. This framework addresses protocols, security, and standards. Digital threads may connect design, development, maintenance, and consumers. Digital threads often work in conjunction with a **digital twin**, a **virtual** representation of a physical object.



Supply chains may also have their own digital twins, which act as a virtual model of every segment of the process. Working with digital twins, a digital thread enables manufacturers to quickly adjust to disruptions or inventory problems. Instead of human feedback, manufacturers often depend on computer-based **algorithms** to manage the constant stream of data. Algorithms can instantly deploy a response to issues along the **digital supply chain** (DSC). As a result, supply chain management in the digital thread environment significantly increases efficiency and reduces the need for human input.

In supply chain management, visibility throughout the supply chain is necessary to maintain **regulatory compliance** with applicable laws and government **regulations**. Increasingly, customers want transparency as well. **Serialization** is one way of providing information about a product throughout the supply chain.



Serialization is the process of assigning unique, sequential identifiers to each distinct unit of inventory that a facility owns or manufactures. Often, these identifiers take the form of **serial numbers**, though they may also be non-numerical tags, such as **radio frequency identification** (RFID) chips.

Serial numbers may be included on individual parts or components, as well as final assembled products. Serialization allows for **traceability** throughout the supply chain, because manufacturers can use serial numbers or tags to track items back to their original production sites. Manufacturers can read the serialized codes either manually or by machine, and can identify which supply chain entities contributed to, stored, or transported the products. Some codes or identifiers may also include data on the specific parts that may have been used in the product's build. Ultimately, serialization allows supply chain partners to track each product's lifecycle.

The traceability that serialization provides helps to guard against **counterfeiting** and **piracy**, which can weaken a product's reputation and hurt business if consumers receive poor-quality fakes. Serialization also allows for quick consumer recall if the manufacturer discovers quality or safety issues with a product or its parts.

In serialization, a unique identifier is added to a part or final product, enabling traceability throughout its lifecycle and ensuring that it is not counterfeit. However, if it is applied as a label or stamp, this identifier could be removed. Using **AM**, a unique serialization structure can be embedded within an additively manufactured part, providing a much higher level of confidence that the identifier will remain intact on the part.

Each AM machine has a specific processing framework based on parameters including part materials, part geometry, and build method. Normally, AM processes are optimized for precise part creation. However, these processing parameters can be temporarily altered to create a unique identifying mark within the part material that is virtually impossible to replicate. Unless the part is broken or cut open, this mark can only be viewed using various **nondestructive testing** (NDT) techniques such as **X-rays**. After a part is manufactured, it would be scanned to record the unique mark. The manufacturer can then keep a digital copy of that scan, which can be used to compare future scans to confirm the part's authenticity.

Serialization can code and identify both manufactured parts and AM machines themselves. Serializing AM machines allows supply chain entities to track elements such as a build's initial designer. It acts as a traceable link between the part and the conditions of its creation.

Like serialization, **blockchain** is a method that increases traceability, accountability, and security against counterfeits and piracy. Unlike serialization, blockchain is entirely digital. Instead of just adding a single, unique identifier to each product or machine, it ties all the identifiers together in a digital chain to make fraud difficult.

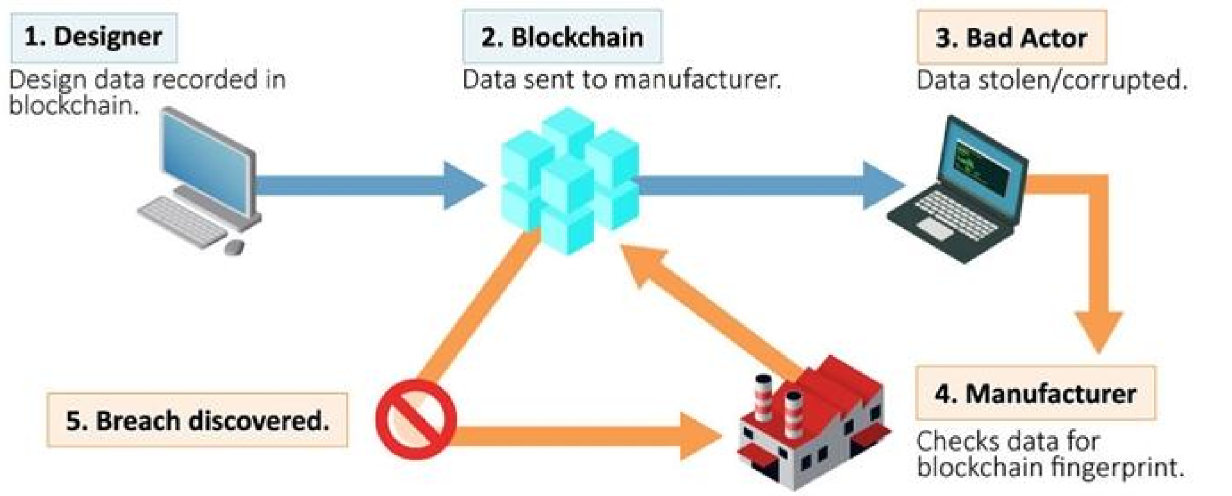
Blockchain technology is a **decentralized**, **distributed ledger**, which means that it is a record stored on a network of computers rather than on a single device. This helps to prevent records from being stolen or destroyed. Blockchain records the **provenance**, or place of origin, of a digital asset.

A block in a blockchain essentially acts as a digital, rather than physical, serial number for an item. Blocks act as links in the chain. Every chain includes several blocks, and each block consists of three elements:

- data about the provenance of the asset.
- a number called a **nonce**. Creating a block generates a random nonce.
- the **block header hash**, a much larger number that is attached to the nonce. Just as creating a block generates a nonce, a nonce in turn generates the block header hash.

Since a blockchain is a distributed ledger, no single individual or site can single-handedly control the chain. Instead, the chain's information is distributed across a network of **nodes**. A node is any kind of computer or electronic device that preserves copies of the blockchain and maintains the functioning of the network.

Every action in the ledger can be reviewed, which makes blockchain remarkably transparent. Each contributor to the chain is given an exclusive alphanumeric identification number that records their transactions. Because of this, all alterations to the blockchain are traceable, which builds user confidence in the chain's integrity.



In traditional manufacturing supply chains, the company that creates a part design would also handle manufacturing and then shipping the part. In the AM supply chain, however, the part designers may digitally transmit design files to other organizations that are part of the supply chain. Although most companies who send digital design files are rigorous about **cybersecurity**, digital transfer always carries risk. Blockchain helps to prevent a design file from being compromised in the event of a cybersecurity breach. Blockchain transactions allow the file's distribution to be authenticated, transported, and recorded. It also enables all members of the blockchain to recognize the origin of the design data.

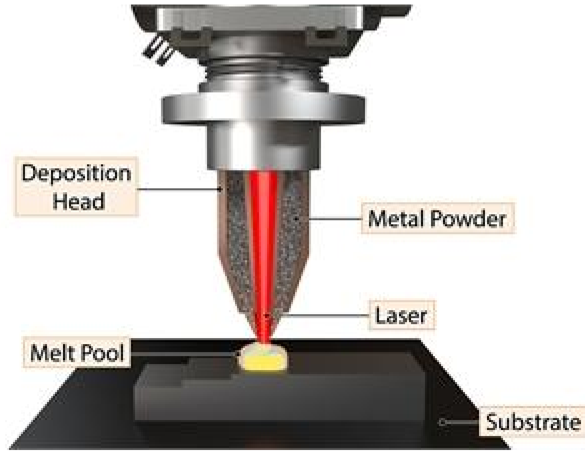
Engineers can also use blockchain to apply production rules to the design files that specify build parameters, including the make and model of the machine allowed to execute the design and the types of build materials permitted. Because the files are sent directly to the AM machines, manufacturers are only able to access the design files once these specifications are met. Additionally, production rules control the number of parts each manufacturer is licensed to print. This ensures that all parts meet quality standards, and it prevents counterfeits from being made on unauthorized equipment. Finally, the blockchain's distributed ledger maintains records of every action and change throughout a design's lifecycle. This allows designers and manufacturers to authenticate a part's origin, which means that any problems in a finished part can be located and addressed in the production process.

261: Hybrid Manufacturing with Directed Energy Deposition

Image courtesy of Hybrid Manufacturing Technologies

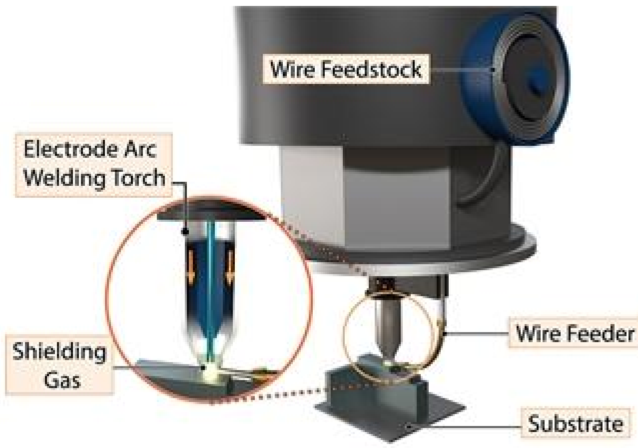
Directed energy deposition (DED) is an **additive manufacturing** (AM) process that builds parts using a **thermal energy source** to melt raw material from powder or wire feedstock onto a surface. Depending on the DED method, the raw material may be dispensed as **feedstock** through a separate device or through a **deposition head** that contains the heat source. Many DED systems use a **robotic arm** to control the tool movements. However, in a **hybrid additive manufacturing** (hybrid AM) application, a deposition head works as a **print head attachment** for a **computer numerical control** (CNC) machine or as a pre-installed component on an all-in-one **hybrid machining center**. Hybrid AM combines additive with traditional CNC machining methods on one hybrid machine. Due to its high deposition speed and relatively simple integration, DED is the most commonly used AM technology in hybrid AM.

Hybrid DED applications generally use either an **electric arc** or a laser as a thermal energy source.



Laser Metal Deposition

The most commonly used **DED** method in hybrid AM machines is **laser metal deposition** (LMD). LMD, also known as direct metal deposition (DMD) or laser deposition welding (LDW), uses a laser as a thermal energy source. In LMD, a **material hopper** dispenses powdered metal through channels in a deposition head. A laser inside the head melts the powdered metal into a **melt pool** using intense heat. LMD typically uses a **shielding gas** to prevent contamination of the melt pool. Because LMD emits both heat and raw material from a single device and does not require a **ground**, it is the easiest to integrate and deploy inside a **CNC** machine.



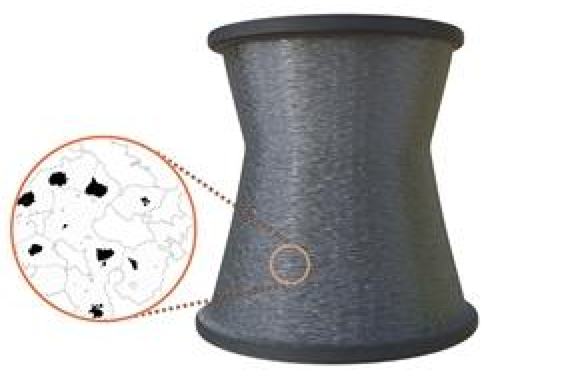
Wire Arc Additive Manufacturing

An **electric arc**, as used in conventional welding, is also a common thermal energy source for DED. The most common welding tools for hybrid DED are **gas metal arc welding** (GMAW) tools, which use the feedstock as a **consumable electrode** to create the arc. Some hybrid machines use **gas tungsten arc welding** (GTAW) tools, which create the arc using a tungsten, **nonconsumable electrode**. Arc welding uses a shielding gas and typically uses wire as a feedstock. When used for DED applications, it is often promoted as **wire arc additive manufacturing** (WAAM). Since wire feedstock is usually a lower cost than metal powder, WAAM is often used to produce larger builds than powder DED methods. However, arc energy sources can also use metal powder as a feedstock.

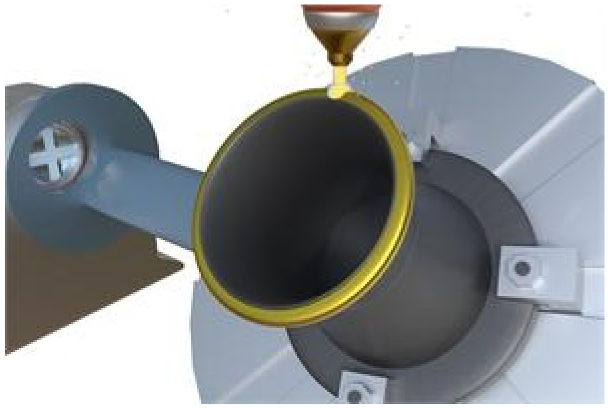
Typically, DED allows faster **build rates** than other metal **AM** methods such as **powder bed fusion** (PBF). DED tools also create larger builds than PBF, giving manufacturers a wider range of part size options. Often, DED can be used to deposit thin wall components more effectively than other manufacturing methods. As a result, DED can be ideal for building large, lightweight metal parts. Additionally, DED requires far less feedstock material to run than a PBF system, so upfront costs for materials are lower.

By controlling temperature and other parameters for DED, manufacturers can improve the **microstructure** of the metal as it cools to optimize **mechanical properties** like strength and hardness. DED tools can also deposit a variety of metals from different feedstocks in precise areas of a workpiece. This optimizes the production of parts containing multiple metal types and also enables deposition of **metal matrix composites** (MMCs). A manufacturer can model a new part containing a variety of metals and MMCs, and the DED tool can build the part directly from the model in a single process.

DED tools can also print additional material layers onto an existing workpiece effectively. This allows manufacturers to customize existing parts in order to optimize certain mechanical properties and improve performance. For example, a manufacturer may use corrosion-resistant metals like **cobalt** or **nickel** to build areas of a part that typically experience heavy stress or wear during use, such as a **flange** or **bearing** component.



Adjusting DED operating parameters can potentially improve the microstructure of part builds.

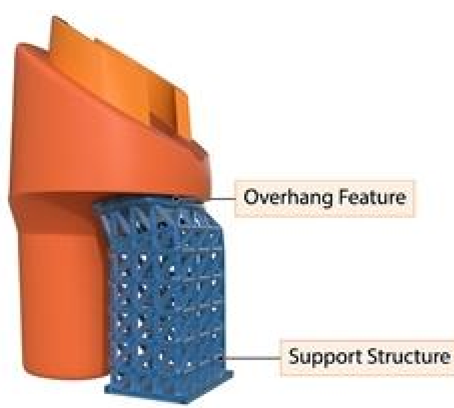


DED machine tools can apply multiple metals in a single build process.

The benefits of DED also come with a number of production challenges. Like other AM methods that use melting, the deposited metal shrinks as it cools. For this reason, part features that require precision such as holes, threads, and **mating parts** are difficult to produce without **post-processing** methods like machining. Metal shrinkage can also cause **variability** from one part to the next. However, building thin-walled, symmetrical parts with DED helps keep cooling uniform to reduce variability and also balance out **thermal stresses** that occur during the build process.

Unlike PBF systems where the build rests in a bed of reusable powder that can support various overhanging part **features**, standard DED systems cannot normally produce overhanging part features that are greater than a 45-degree angle without building **support structures**. However, while non-metal AM processes like **fused deposition modeling** (FDM) often use support structures, most DED applications do not use support structures because they create metal waste that can negate the cost savings of using DED. Manufacturers can use multi-axis machines to reorient the part in order to produce some overhangs. However, even on a multi-axis machine, DED still cannot create planar bridging features. This and the larger scale resolution of DED means that parts are typically less complex than those produced by PBF.

While DED tools have faster build rates than other AM methods, they also print part surfaces at a lower **resolution**. However, this and many other challenges of DED can be overcome with hybrid manufacturing.



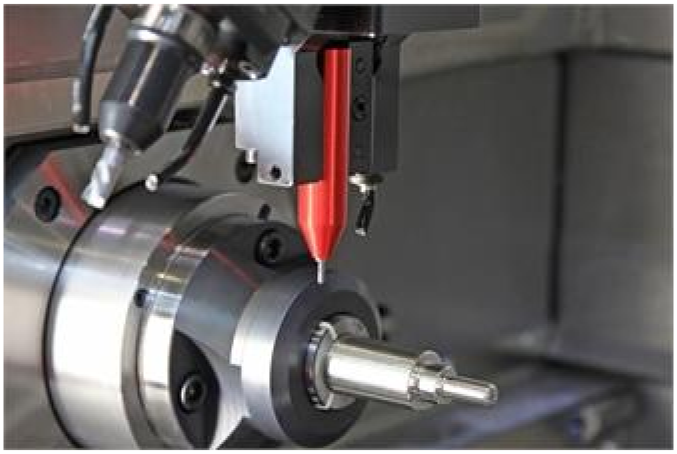
FDM parts commonly use support structures that would be costly with DED.

Low print resolution results in a rough part surface.

In most hybrid AM applications, DED tools are combined with subtractive manufacturing tools on a single machine. An increasing number of hybrid DED machines with CNC capabilities are becoming available on the market, though installing DED tools on traditional subtractive CNC machines to make an all-in-one hybrid machine is also a common approach.

CNC Milling Setup, courtesy of Hybrid Manufacturing Technologies

In hybrid DED part production on a **mill**, the required deposition heads can be installed alongside the **spindle** or loaded directly into the **automatic tool changer** (ATC), which can then load it into the spindle for operation. Loading the head in the spindle allows for deposition directly on the spindle centerline. The ability to use multiple heads in the spindle also enables greater flexibility for different processing types. Before running a **part program**, an operator secures a **substrate** or workpiece onto the worktable using a **vise**, **clamps**, or other **workholding** device. Then, the operator runs the part program, which controls the **toolpaths** and tool changes required to produce the part. The deposition head prints different layers of the part, and cutting tools remove material from the printed layers based on the part program, which is often specialized for hybrid DED.



CNC Turning Setup

Some hybrid DED systems use a CNC **lathe** or **turning center** setup. In hybrid DED part production on a lathe, deposition heads are installed in a **tool turret**, often with a **live tooling** setup alongside cutting tools. An operator then secures a cylindrical workpiece in a three- or four-jaw **chuck**. The chuck is attached to a spindle which rotates the workpiece at different speeds based on commands in a part program or operator commands. The spindle rotates slowly or stops while the deposition head in the turret prints layers of material onto the workpiece, and it rotates at higher speeds while the turret moves stationary cutting tools into the workpiece. Layers of material are added and machined based on the part program.

LMD Attachment for CNC Machine, courtesy of Hybrid Manufacturing Technologies

DED is one of the lowest resolution AM techniques available, which enables it to have one of the highest deposition rates of all AM techniques. However, these high deposition speeds also produce parts with the least fidelity to the digital model of the desired part. For this reason, parts made by DED virtually always require building slightly larger than the model dimensions, then machining as a post-processing step. This two-step approach can be simplified into the same setup on a hybrid DED and CNC machine.

Of the various DED energy sources and options available, **LMD** is currently the most widely adopted for use inside of hybrid machines. This is partly because using a laser as the energy source provides the highest quality metal deposition with the lowest heat input into the substrate, resulting in fine-grained microstructure. Using a laser also eliminates the need for grounding the part as is required for arc-based DED approaches. Since DED deposits metal at only a single point, the existing **G code** and **M code** programming style, which controls **toolpaths**, tool changes, and other machine functions, is well suited for programming DED. As a result, traditional CNC programmers and machine operators will require less technical training when converting from traditional machining to a hybrid LMD process.

The faster build rates of traditional DED tools come at the expense of lower print resolutions. However, hybrid DED tools take advantage of the faster build rates while using subtractive machining methods to compensate for low resolution. Operators can simply use DED to build different areas of a part slightly larger than specifications, then machine each area to the specified dimensions. This also addresses variability effectively, as machining each part down to size cuts away any size variations that may occur during cooling. Hybrid DED thus allows manufacturers to build parts with tight **tolerances** faster and more efficiently than other methods.

DED typically minimizes the use of support structures since it creates metal waste. Since there is also no powder bed or built-in support method, this can limit the types of part features traditional DED tools can produce. However, hybrid DED tools that use additional axes to rotate parts can compensate for this drawback. **Four-axis** or **five-axis** machining permits the movement of tools in three axes as well as the rotation of the workpiece. With four or five-axis flexibility, deposition heads can access parts from multiple angles, so operators can print on layers of the part that are unreachable otherwise.

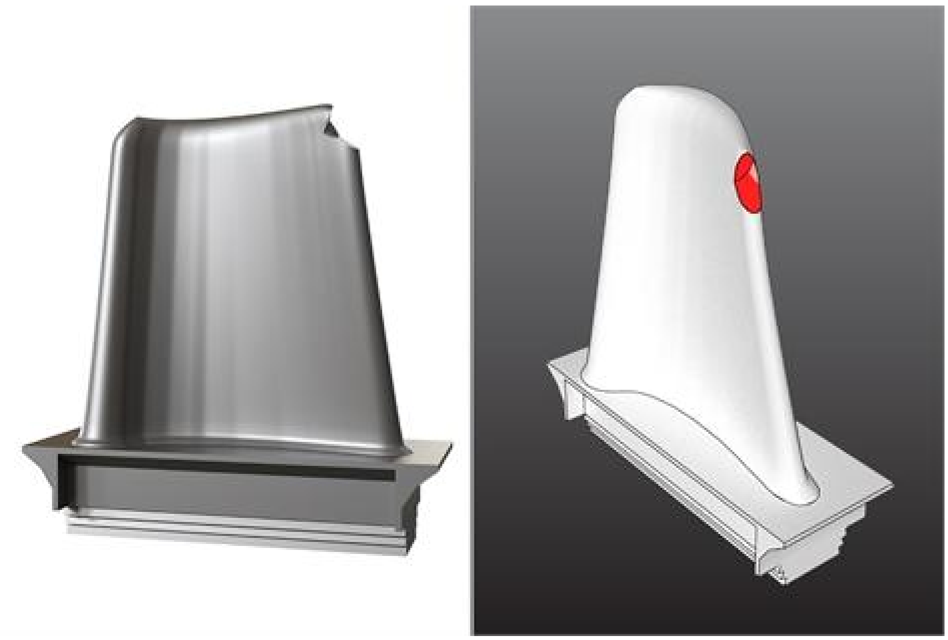
Some manufacturers use hybrid DED systems in order to build parts to **net shape**. A net-shape part is a part built to its final, specified dimensions and requires no further processing. While traditional DED can only build parts that are **near net shape** without post-processing, hybrid DED combines the AM and post-processing steps into a single, streamlined process.

To create a net-shape part with hybrid DED, a manufacturer first designs a specialized part, such as a rocket nozzle, using **computer-aided design** (CAD) software to create an **stereolithography** (STL) file. The manufacturer then uses a **computer-aided manufacturing** (CAM) software package that can translate the STL file into a part program that includes toolpaths and tool changes for the deposition head as well as machining and finishing tools. Hybrid DED typically uses G code part programs.

Next, an operator or robot loads the appropriate tools and material feedstock onto the machine. The operator then establishes **part zero** on the subtrate or **build platform**, which is the bottom of the part and acts as the origin point for all machine movements in the part program.

Finally, the deposition head deposits layers of material onto the substrate or build platform, and cutting tools machine the layers to correct dimensions based on the CAD model. The part program often alternates between DED and machining until the part is built and finished to net shape.

While hybrid DED can build specialized, net-shape parts effectively, it is more commonly used to build part features onto an existing workpiece. In this process, a manufacturer creates a **CAD** model of a part, such as a jet engine **turbine**. Next, hybrid **CAM** software converts the 3D model of the desired part feature, the turbine blades, into programmed toolpaths for the deposition head and finishing tools. The workpiece, an unpopulated rotor, is then loaded onto the hybrid machine using a workholding device. After setting part zero on the workpiece, the operator runs the program. Using precise machine coordinates in the part program, the deposition head prints the part feature onto the workpiece, and cutting tools apply finishing operations as needed to complete the part feature.

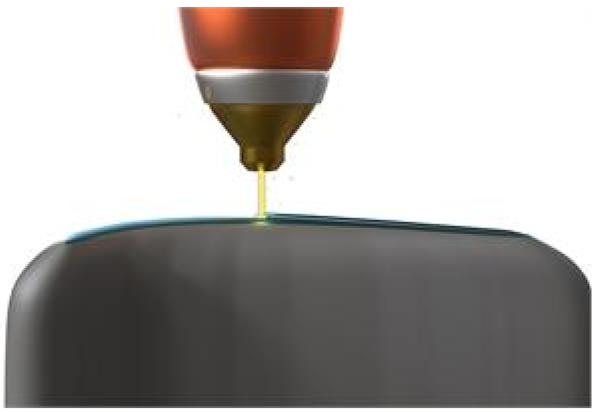


Damaged Part and CAD Model for Repair

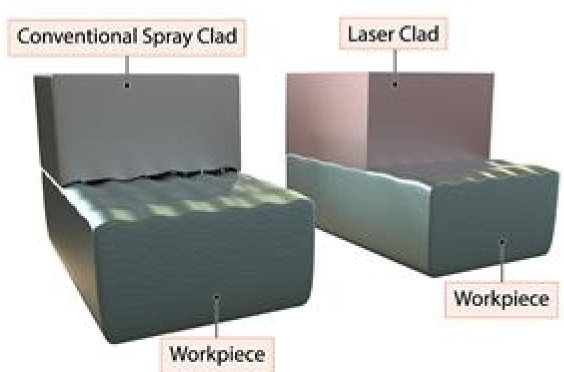
Repairing metal parts is the most common use of DED. While welding and manual grinding is the traditional method for metal repair, hybrid DED allows manufacturers to **automate** traditional repair processes, such as repairing a damaged or worn turbine blade, **blisk**, or **impeller** and finishing the repaired surface on the same machine. To repair a single part, a technician may scan the damaged part with a **laser scanner** or **touch probe** to create a digital model, which is used as the model for the repair. Before repairing the part, a machining tool must remove the worn or damaged material to produce a clean surface at a known dimension. This machined surface becomes the initial build surface for adding material to rebuild the part using DED. Since DED produces a relatively rough surface finish, the deposition process should always overbuild the replaced part so that it is slightly larger than the final part dimensions, or near net shape. Lastly, a finishing tool removes a precise amount of material to finish the printed part surfaces to the part's final size, or net shape, using subtractive methods. A critical aspect of final machining is that the added repair surfaces should blend into the original part surfaces with very little mismatch. In a hybrid DED and CNC machine, this mismatch can often be minimized to less than 20 **microns**.

Like repair processes, manufacturers often use hybrid DED systems to add material **coatings** to parts and components. This process is often referred to as **laser cladding**. A material coating may be included as part of an original part design to increase **wear resistance** or other properties. Coatings may also be added to existing parts to add properties that were not present in the original part material, or that were lost due to wear. For example, coating a part with a **superalloy** can improve its strength, heat resistance, and other properties. Since superalloys are very expensive materials, coating the part costs much less than building the entire part from the superalloy. This is just one aspect of the overall cost savings, as applying certain coatings to part surfaces can also greatly extend the life of the part.

Unlike traditional **cladding** methods that use **cold spraying** or **thermal spraying** techniques, laser cladding with DED can create a **metallurgical bond** between the part and the coating metal. This metal bond is more durable than traditional cladding that only forms a **mechanical bond**. Laser cladding can also bond some dissimilar metals such as **Inconel** and steel more reliably and easily than alternative cladding methods. Laser cladding on a hybrid DED system also allows each layer to be machined to precise dimensions and finished to reduce surface **asperities** and variability before bonding the next type of metal.



Laser Cladding



271: Lightweighting with Additive Manufacturing

Lightweighting is an increasingly popular practice in manufacturing. Lightweighting reduces the weight of parts while ensuring that the parts' functions remain the same. This serves two primary purposes. First, reducing the weight of a product means it requires less energy to move it, both during shipping and during the part's use. Second, using fewer or lighter-weight materials reduces costs and uses fewer resources.

Lightweighting involves **continuous improvement** as manufacturers regularly seek to further reduce the weight of their products. What was once considered light soon becomes an area of potential improvement. Lightweighting begins as a design strategy. Engineers constantly test new designs for achieving lighter weights without loss of functionality. Lightweighting a part can also affect the design of other parts or components. For example, shifting from steel to a lighter aluminum automobile body may require other changes to the car's design, such as updating paints, adhesives, and welding processes.

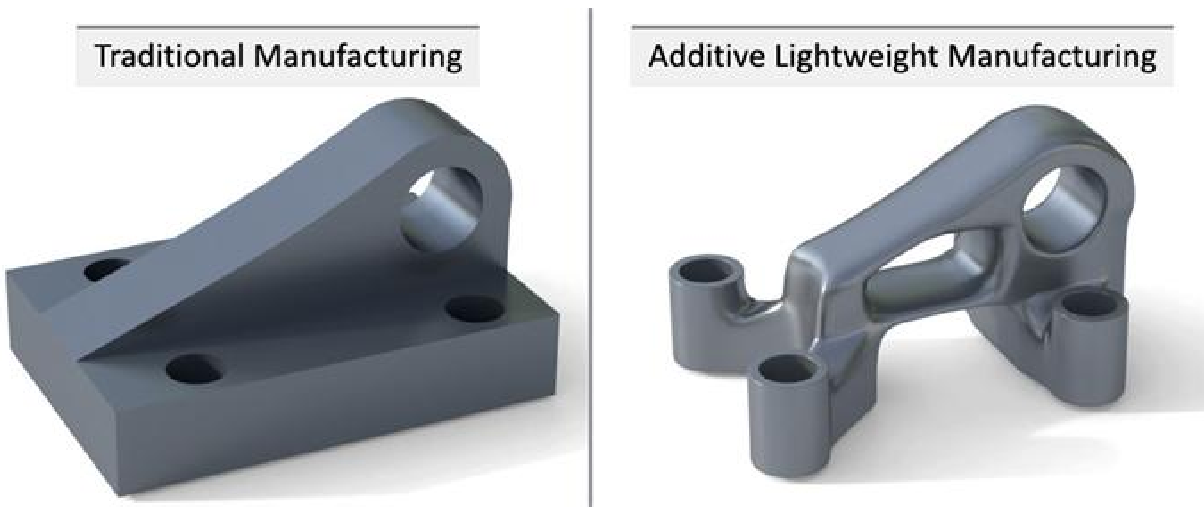
Replacing steel parts with aluminum is an example of the popular lightweighting method, **material substitution**. Lightweighting parts by substituting plastic or **carbon fiber** instead of metals, for example, has been a long-standing trend, particularly in automotive manufacturing. Recently, however, automakers and other manufacturers are recognizing that material substitution alone may not be enough to reach their lightweighting goals. **Additive manufacturing** (AM) offers more flexibility than material substitution or traditional manufacturing methods, so manufacturers are increasingly using AM methods to lightweight parts.

This material is based upon research supported by, or in part by, the U.S. Office of Naval Research under award number N00014-18-1-2881 led by the National Center for Defense Manufacturing and Machining (NCDMM).

An auto part made of lighter-weight carbon fiber materials.

An additive manufacturing process.

Lightweighting can be achieved by multiple methods other than material substitution. **Material reduction**, or creating parts of the same functionality but with smaller amounts of material, is another effective method. **AM**, which builds parts up in layers, is an ideal way to achieve material reduction.



Today, several industries use AM to develop and produce lighter parts. The design and build processes of AM allow for lightweighting to occur at multiple steps in the manufacturing process. Software for AM assists in identifying material reduction opportunities in the design phase. AM build processes can produce structures with less **density** than traditional processes.

In additive manufacturing, an AM machine builds a finished part by stacking and joining layers of material. AM parts often have improved complexity and functionality compared to parts manufactured by traditional processes like **machining**. Unlike traditional manufacturing, which is limited by things like the size and shape of cutting tools, AM can lay down layers in unique, precise ways. Rather than starting with a solid block of raw material that must be cut or shaped, AM processes can deposit material only where it is necessary, which gives designers much more flexibility to reduce part material.

AM capabilities and modern software give part designers much more flexibility. Currently, manufacturers recognize seven distinct AM methods, three of which are commonly used for lightweighting. Key AM methods for lightweighting include **directed energy deposition** (DED), **material jetting**, and **powder bed fusion** (PBF).

Directed energy deposition uses a **laser** or other source of focused **thermal energy** to melt and fuse materials in order to create a part layer. During DED, a **deposition head** focuses and directs thermal energy at a base, which can be a build platform or a **substrate**. In the deposition head, there is also a nozzle that feeds build material into the thermal energy. When the energy source and build material contact one another at the base, a **melt pool** forms. As the deposition head moves across the base in the shape of the desired part, the melt pool travels with it, creating a material layer that gradually solidifies upon removal of the energy source. DED creates parts by repeatedly passing over the base to build up layers of material.

Material jetting uses **ultraviolet light** (UV light) to cure **photopolymer** build material. During material jetting, one or more **print heads** move horizontally over the build platform to deposit a layer of build material in the shape of a part. The build platform then lowers, and the print heads deposit a new material layer onto the previous layer. Each layer solidifies and binds together. This process repeats until the part is complete.

Powder bed fusion uses focused thermal energy to selectively fuse layers of powdered build material. During PBF, a roller dispenses a layer of powder onto a build platform within a powder bed. An **image projection module** focuses thermal energy and projects it, moving it in the shape of a part across the powder layer. Contact with the thermal energy fuses the powder particles together and forms a part layer. Then, the roller dispenses a fresh layer of powder over the first, and the process repeats until the part is complete.

Advances in AM are enabling parts to be manufactured faster and more cost-effectively. Several industries use AM to develop and produce lighter parts, resulting in savings on raw material costs, among other benefits.

Lightweighting is a top priority in the automotive industry. The goal of reducing overall vehicle weight is to improve **fuel efficiency** and meet the needs of newer electric vehicles. Under most circumstances, a ten percent reduction in vehicle weight can lead to an eight percent improvement in fuel efficiency. However, lightweighted parts must still meet the same rigorous safety and performance standards as traditional parts.

The aerospace industry also considers fuel efficiency a prime concern. Reducing the **mass** of aircraft can reduce fuel consumption because a lower mass requires less **lift force** and **thrust** during flight. In addition to reducing an aircraft's **carbon footprint** and operation costs, lightweighting can help to achieve flight performance improvements such as increased safety, better acceleration, and higher structural strength.

In the medical industry, equipment must provide faster, more accurate, and easier-to-manage ways for care professionals to treat patients. Lightweighting improves the durability and functionality of components for patient monitoring equipment, advanced robotics, **prosthetics**, replacement joints, dental implants, and surgical tools. Lighter products can also have increased portability and accuracy.

Energy industries also see increased efficiency with lightweighting. For example, to generate wind power using **wind turbines**, manufacturers use extremely lightweight materials to create long rotating blades. When the wind rotates the blades, they transform the wind energy into rotating energy that is then transformed into electricity. High wind speeds and the size of the blades place the blade material under high **stress**, which can lead to performance issues or failure. Lighter weight blades have less **inertia**, and thus experience less stress when turned by the wind.

Compared to traditional manufacturing technologies, which rely on rigid tools to cut or shape raw materials, AM has far fewer design limitations. For example, a drill is only able to cut in a straight line, while AM can build up parts with holes that curve around other part features. This increased flexibility means that designers can focus on optimizing part function.

A designer creates a part model on CAD software.

Design for additive manufacturing (DFAM) refers to designing a part or a product for effective and efficient AM. DFAM includes **system design**, which considers which parts should be manufactured using AM and what the parts should look like.

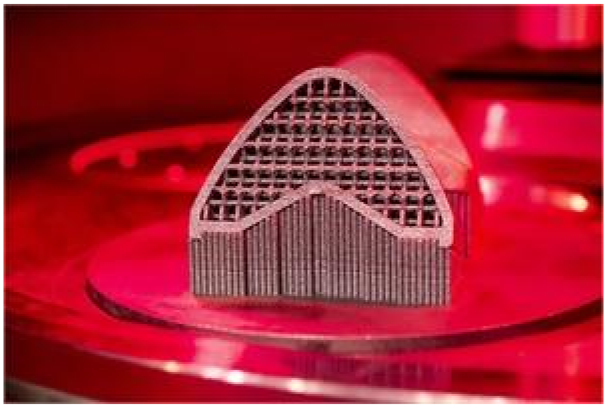
Most essential to lightweighting processes is **part design**, a stage of the DFAM process that determines the best geometric design for a single part based on performance requirements, such as whether or not the part must support weight or resist impacts. Designers use **CAD software** to create and virtually test models of a part, including removing material for lightweighting purposes. When a designer removes material at the CAD level, it is critical that they confirm that the part possesses all the necessary properties, such as strength and safety.

Reducing the mass of a part impacts every other mechanical aspect of its design. Without careful consideration, lighter parts may not meet the same **tolerances** as their heavier counterparts. Manufacturers must ensure that lightweighted products still meet safety, durability, and performance standards.

Since AM is able to deposit or fuse material specifically where it is needed, it allows engineers to design parts that use the precise amount of material required to perform. Rather than beginning with a block of material and cutting away material to shape it, AM processes can create parts with gaps or hollow areas anywhere that strength or other properties are unnecessary. This greatly reduces material waste, but it also leads to parts with unusual shapes.

Because hollowing or eliminating areas of a part can impact its strength and durability, designers must test product designs using **simulation software**. Traditional simulation tools provide details on digital part models, including areas of stress or strain. Lightweighting often requires a specific type of simulation software that can calculate **topology optimization** (TO). Topology optimization software uses a mathematical method to optimize a part's material layout. Designers enter aspects of the part's intended use, such as the **loads** it will bear, and the software calculates exactly how much material to use in different areas of the part to meet those requirements. TO can recognize the sections of a part that are the least necessary to its overall strength and recommend eliminating those sections. This speeds up the design process significantly and greatly reduces the time necessary to test physical parts and refine part design prior to production.

In addition to the design advantages provided by topology optimization, the ability of AM to create **lattice structures** is also advantageous for lightweighting. Similar to **TO**, lattice structures allow designers to avoid the weight of fully dense parts while maintaining their strength.



A lattice is made of repeated **unit cells**. These cells can take a variety of shapes and sizes, and they may be repeated in many different ways. A **uniform lattice** has identical cells repeated in every direction, while a **variable lattice** has cells of varying size or spacing in different directions. Both kinds of lattice structures can maintain internal support in an AM part, which means that the part can be lighter weight while retaining strength. The weight savings improve the part's **strength-to-weight ratio**.

A benefit of lattice structures is they can be additively manufactured faster, using less material and requiring less build time than fully dense, solid components. This improved material use may allow cost-effective use of higher-quality, more expensive materials. Since traditional machining operations start with a solid block and cut material away to create a part, creating a lattice structure would not reduce the amount of material required. However, AM can build lattices without significant waste or excess up-front material expense.

AM technology makes it possible to design and manufacture high-strength, lightweight structures where traditional manufacturing cannot. This has several advantages, but adapting to lightweighting with additive manufacturing can also present some challenges.

AM processes remove some of the extra material required in traditional manufacturing. During production, the AM machine deposits or fuses material only where it is functionally necessary, and unused materials leftover from builds can often be reclaimed and reused in future builds. Lightweighting with AM thus requires less build material overall, which reduces material costs. Additionally, AM can build solid parts from multiple materials. This means that AM can deposit expensive materials only where needed instead of building the whole part from them, which also saves material costs.

Lightweighting results in parts and products that use less energy, making them more environmentally friendly, which is a concern among many conscious consumers and company leaders facing environmental regulations. Transporting and shipping parts and products of lighter weight also saves energy resources.

Lightweighting with AM results in parts that are often at least as strong as heavier, traditionally manufactured parts. This is a benefit of the topology optimization process, which allows designers to remove materials without sacrificing part strength and integrity. The complex geometric structures that AM enables also yield more durable results, such as the improved strength-to-weight ratio found in lattice structures.

Rovers, satellites, and other objects that travel or carry items to space have strict weight limits. Lightweighting can allow them to carry far more equipment than a heavier version could because lightweighting spares more space for additional functional instruments and batteries. These add-ons can increase both functionality and powered-up time in space.

Despite its numerous benefits, lightweighting creates challenges for AM. Even if lightweighting may save on material costs, it requires up-front investment of time and money. Adapting production lines for lightweighting purposes can include purchasing new equipment and taking time to modify processes. As manufacturers introduce new lightweighting processes and materials, they must also provide new training for their employees and anticipate **learning curve** delays. Additionally, additive manufacturing processes may not be well suited to mass-scale production or building large components, both of which are important in industries like automotive and aerospace. Further, because AM technology is still evolving, part testing and **inspection** are not fully standardized, which can also slow mass production and make it difficult to build large parts safely.

291: Additive Manufacturing Qualification

The rapidly emerging technologies of **additive manufacturing** (AM) are gaining recognition due to their many strengths and advantages. Most commonly, manufacturers use AM for **rapid prototyping**. Rapid prototyping produces prototypes of new designs much faster and with far fewer resources than **traditional manufacturing** methods. However, as AM technologies evolve, manufacturers are capitalizing on other benefits of AM, particularly its enhanced design capabilities. AM methods can produce parts that are difficult or impossible to produce using traditional methods. Using additive also generally reduces material costs and simplifies supply chains. Many manufacturers seek to leverage the flexibility of additive technologies for more **end-use** products, and the prospects of lower material costs and simplified supply chains have motivated manufacturers to pursue AM production at a larger scale. However, AM presents a number of **quality assurance** (QA) challenges for manufacturers. In order to produce end-use parts with AM, organizations must overcome these challenges and adopt or develop robust quality assurance measures for qualifying end-use AM parts.

To help ensure the quality of end-use products, manufacturers rely on **standards** to qualify a wide range of manufacturing materials, parts, and processes. General manufacturing standards can include **certification** requirements for machine operators and **maintenance** personnel, machine temperature limits for certain materials, safety measures, and performance testing requirements for final parts.

Aerospace component manufacturers must often meet the highest quality and **safety standards**. Aerospace parts have very tight **tolerance** specifications to ensure proper fit and functionality. Tolerance describes the permissible amount of deviation from a specified dimension. Tight tolerance requirements can limit the use of **AM** methods for building end-use aerospace parts since many AM machines alone cannot produce parts that meet these tolerances. Additionally, **QA** strategies for traditional manufacturing processes are often not sufficient for qualifying AM processes. For this reason, some organizations have developed new standards for AM part production.

ASTM International has coordinated with the **International Organization for Standardization** (ISO) to publish standards defining specific AM processes and terminology, general material selection and processing protocols, and some specific material- and machine-related guidelines. Currently, most AM-specific standards are related to aerospace.

Jet Turbine

Rocket Engines

While aerospace standards are the most rigorous, safety and performance requirements are also top priorities for other industries

Similar to aerospace, automotive parts must meet safety and quality standards. While no current automotive standards focus specifically on additive manufacturing, AM parts and processes must adhere to automotive industry standards, such as **IATF 16949:2016**. This standard, which replaced **ISO/TS 16949**, provides guidelines for quality assurance of auto part production, installation, and maintenance. The standard requires manufacturers to show that they can use **quality management systems** (QMS) to meet customer and regulatory specifications.

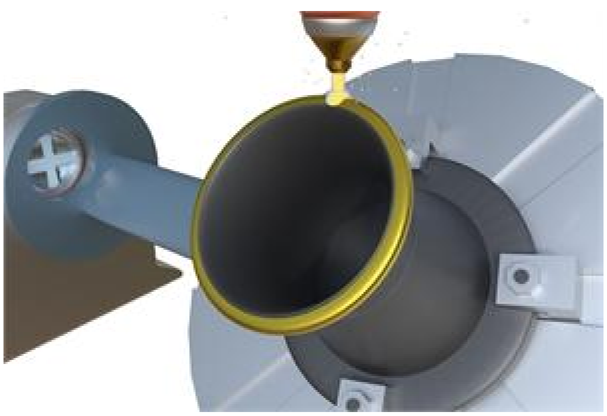
The medical industry is a primary adopter of AM. AM is commonly used for rapid prototyping and can also be beneficial for various end-use medical products, such as containers, tools, and even **surgical implants**. By using **reverse engineering** to create a digital model of a person's limb, AM machines can build customized **prosthetics** from **ceramic**, metal, or **polymer** materials. While these enhanced design capabilities are promising, additional standards are needed to qualify parts for the medical industry due to the dangers of **contamination** and other safety issues. Currently, standard **ASTM F1537-20** specifies QA requirements for a type of metal wire commonly used in surgical implants. Ensuring the integrity of materials helps ensure the mechanical properties of the finished parts. Some **directed energy deposition** (DED) methods use metal wire and could be used to make these implants. However, the manufacturer would need to ensure the material retains its desired properties according to the ASTM standard after it has gone through the DED process.

The defense industry is also adopting AM technology to improve design efficiency, performance, and **supply chain management**. Defense uses a range of equipment that can be made with AM, including aerospace and automotive components as well as medical equipment, and may adopt quality standards from each respective industry. One U.S. defense standard that applies specifically to AM is **MIL_STD 3049**. This standard applies to parts repaired using **direct metal deposition** (DMD), a type of directed energy deposition. The standard provides guidelines for the repair process as well as the inspection and testing of the repaired part.

In addition to following general guidelines established by current standards, manufacturers must develop in-house quality management strategies for qualifying AM operations. Each AM process has unique design and production capabilities that are not addressed in many current standards. Additionally, the wide range of available AM machines and methods make AM processes difficult to standardize. This can create **regulatory compliance** issues that limit the use of a range of versatile AM technologies to create aerospace or other sensitive components. Because quality goals may not be achievable with some AM processes using traditional manufacturing standards, these processes require new considerations that are not addressed by traditional qualification strategies.

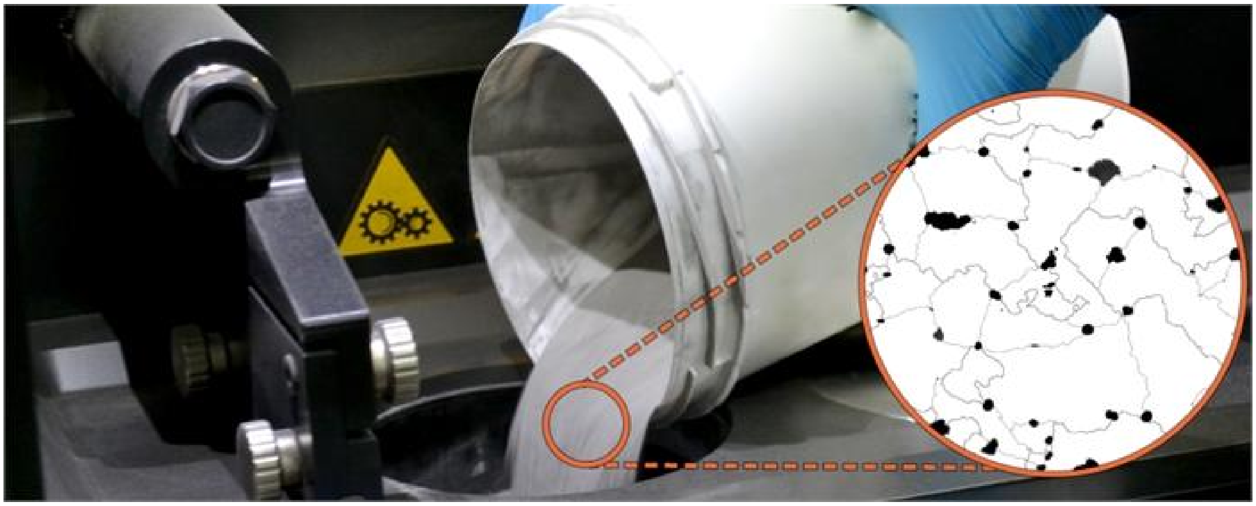
Some standards, like those developed by the **American Welding Society** (AWS), address general guidelines for all AM processes. The AWS Specification for Fabrication of Metal Components (AWS D20.1/D20.1M:2019) standard presents guidelines for designing, building, and inspecting metal AM parts. However, manufacturers must still develop qualification strategies that are specific to their own operations at each production stage for the wide range of AM processes. Other current standards guide the selection and qualification of materials before they are processed, but AM methods often alter material **properties** during and after the build process. Some published standards aim to address AM qualification processes for more specific applications, like using **DED** for part repair and building consistent **net-shape** parts using **laser powder bed fusion** (L-PBF) and **binder jetting**. However, additional standards are needed for these and other AM technologies to qualify a part's material and mechanical properties throughout each build process.

Unique AM parts may require new qualification strategies.



Current standards address DED repair and some other AM processes.

Manufacturers should select **raw materials** intended for end-use parts based on approved qualities. Current standards cover various aspects of material selection, but manufacturers must also consider how the build process will affect the selected materials’ properties.



AM qualification may require examination of a material's microstructure before, during, and after a build.

The **National Aeronautics and Space Administration** selects raw materials for aerospace components based on the **useful life** specification. This means selecting only those materials that can withstand expected operating temperatures, loads, and other conditions for the intended **lifecycle** of the part. Another standard, **ASTM F2924-14** suggests that different powders may require different testing methods based on material type, particle size, and other factors. Other material standards include the **Aerospace Material Specifications** (AMS) developed by **SAE International**. Standard **SAE AMS 7002-2018** covers general processing guidelines for metal powder feedstock for AM, while **SAE AMS 7001-2018** provides guidelines for a specific nickel-alloy powder that is resistant to corrosion and high temperatures.

Though it is important to qualify raw materials selected for AM processes, manufacturers must also be able to qualify parts built using AM. Many AM build processes can alter the properties of **build materials**, which can affect the intended **mechanical properties** of finished parts. Metals and polymers especially undergo various material changes during the heating and cooling phases of high-temperature AM processes. Each material has a different **glass transition temperature** and **melting point**, and manufacturers must develop systems to verify material integrity is maintained consistently during and after different build processes. **Metallurgy** can often be used to determine material properties and integrity by examining the **microstructure** of materials at different stages of the build process.

Qualifying any production method requires manufacturers to repeat the same quality results each time a part is produced.

When using any AM processes for end-use parts, manufacturers must adopt measures to increase **repeatability** and reduce **variation** to acceptable levels based on production standards. Repeatability can be difficult to achieve with AM machines. Machines may produce different results depending on temperature settings and material type, as well as **layer width** and other adjustable variables. In order to help achieve repeatability, machine operators must fine-tune variables such as layer width and other settings. Design engineers and machine operators must collaborate and use **troubleshooting** skills to achieve desired results by performing repeated experiments. This process must be optimized until an acceptable level of repeatability is achieved. Specifying machine settings based on optimized **build parameters** reduces or eliminates the need for repeated experiments, streamlines training of new technicians, and increases productivity.

In addition to machine settings and operating procedures, AM machine **maintenance** procedures must also be standardized. Maintenance technicians should be certified according to relevant industry standards or in-house standards when no concrete standard exists.

Manufacturers using AM must adopt standards to address quality and repeatability challenges at every stage of **design for additive manufacturing** (DFAM).

In the designing phase, design engineers create digital part models using **computer-aided design** (CAD) software. A standardized CAD process for each AM method helps improve quality assurance. CAD software has settings for specific AM machine types, many of which must be adjusted based on part specifications, so design engineers and technicians should understand the capabilities and limitations of each machine that will produce a final part. Some advanced CAD software has additional functionality, like complex algorithms for **topology optimization** and **generative design**. Other more basic CAD tools, like free downloadable software packages, may not be sufficient for complex, end-use part production. Manufacturers should determine software functionality requirements based on quality standards for each part.

Standardizing **workholding** and machine setup processes for AM is also a challenge. The complex part geometry that some AM methods can produce is not always supported by traditional workholding devices. Though AM build processes do not require workholding, the complex shapes created with AM can hinder or prevent traditional hardness testing and **post-processing** methods without specialized workholding devices. Manufacturers may need to adopt nonstandard custom workholding methods, such as using **adhesives** or customized **grippers**, for uniquely shaped components.

Build processes for different machines should also be standardized. Most current standards for AM machine qualification cover **L-PBF** machines. For example, **ISO/ASTM 52941:2020** establishes specific tests necessary to qualify L-PBF machines for metal parts before they can be used for production. SAE International has published standards for L-PBF and binder jetting, a similar method that uses raw material powder and a binder material. Standard **SAE AMS 7003-2018** addresses L-PBF process controls. **SAE AMS 7022** outlines process guidelines for building metal or ceramic aerospace parts with binder jetting. Additional standards must be developed to help qualify a broader range of specific AM processes and applications.

All AM parts require post-processing. AM parts may need **curing** or **heat treatment** to prevent thermal damage, **shot peening** to improve surface strength, or other methods depending on the material, process, and operating conditions. Manufacturers should determine standards for how each part should be heat treated, proper materials for **infiltration**, and other details for different parts and processes.

Unqualified AM machines and processes can produce varied results in final parts. Final part **dimensions** and **surface finish** can vary from one build to the next, even with the same machine settings. Without strict guidelines, some AM processes can also alter the chemical properties and microstructure of a part’s material, which can ruin the part's required mechanical properties and render it unusable.

Hardness tests can be performed on many parts produced with AM.

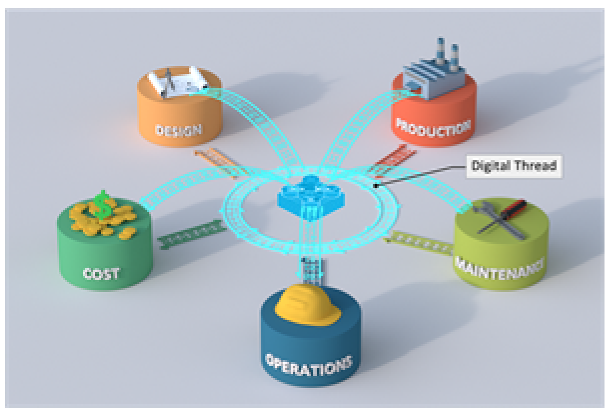
Operators and technicians must perform tests and measurements after post-processing to ensure that a final part meets design specifications and performance requirements. Manufacturers must develop strategies to test and qualify part quality throughout the build process. For example, using **test coupons** to check a part after each step of the build can help manufacturers greatly reduce variation in final parts. Engineers and technicians must fine-tune unstandardized processes to produce a quality part. AM end-use parts, especially safety devices and other critical components, should meet the same safety and quality standards as parts made with traditional methods. Many tests for traditionally manufactured parts, such as the **Rockwell hardness test**, can be performed on AM test coupons and final parts. After standardizing an AM production process, manufacturers can also use **nondestructive testing** (NDT) methods, such as **radiographic testing** (RT) or **ultrasonic testing** (UT), to qualify parts before distributing them for end-use.

Manufacturers using AM must accurately collect and store data, such as preferred machine settings, to qualify specific applications. Data collection provides advantages such as the **digital thread** for product lifecycle monitoring, **predictive maintenance**, and design optimization for future product iterations. The digital thread offers a number of benefits for material quality assurance and machine, process, and part qualification. Creating **internal sensors** in AM parts to record and analyze usage data can also help improve design for future iterations of the part.

Collecting and leveraging data also enables manufacturers to automate processes using **machine learning** (ML) and **artificial intelligence** (AI). **Automation** can greatly improve quality by increasing the efficiency of inspection, maintenance, and other processes. Machine learning and AI also enhance design software, enabling capabilities like topology optimization and generative design.

Most manufacturing processes in **smart manufacturing**, including AM, rely on the **Industrial Internet of Things** (IIoT). The IIoT includes a range of smart technology devices, such as **sensors** for data collection, cameras and scanning devices for reverse engineering, connected AM machines for streamlined production, and local and **cloud computing** devices for data storage. When connecting AM machines to the IIoT, manufacturers must protect **proprietary** and confidential information such as designs and specialized materials. Additionally, since most machines communicate digitally with other devices, manufacturers must be cautious of **malware** and other cyber threats that could affect machine operation. All IIoT devices are susceptible to malware and other types of cyber attacks, which can completely stop production or even create safety hazards.

Generative Design Software



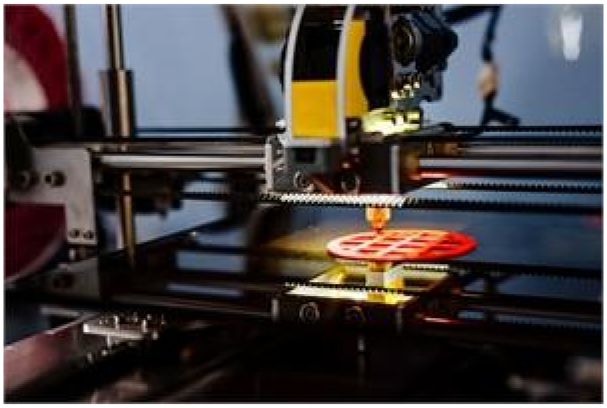
Digital Thread

301: Design for Fused Deposition Modeling

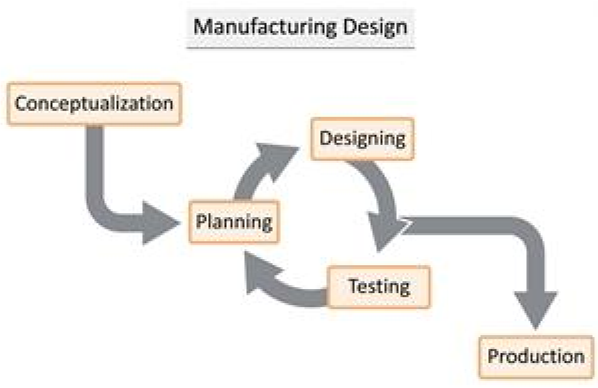
Fused deposition modeling (FDM), a type of **material extrusion**, is also known as **fused filament fabrication** (FFF) and is one technique in a larger group of building methods referred to as **additive manufacturing** (AM). FDM machines use a nozzle to dispense melted part material onto a build platform. Because FDM is the most widely used AM technology, it is commonly associated with the term **3D printing**. The FDM process is used in **desktop** hobbyist, or consumer-level, machines as well as large industrial-level machines for **end-use** production.

Although each AM method requires specific equipment to build parts, they all share the same basic five steps of the **design for additive manufacturing** (DFAM) process: **conceptualization**, **planning**, **design**, **testing**, and **production**. The flexibility of FDM and other AM methods enables engineers to consider things like part functionality, optimizing complexity, and customization when designing for AM. The planning, designing, and testing steps also offer AM designers opportunities to increase production efficiency, since creating a **prototype** does not require additional tooling or machine configurations.

This material is based upon research supported by, or in part by, the U.S. Office of Naval Research under award number N00014-18-1-2881 led by the National Center for Defense Manufacturing and Machining (NCDMM).



The FDM Process in Action



DFAM Steps

Extrusion is the process of forcing material through an opening, such as a nozzle. In the **FDM** process, extrusion begins with pellets or spools of raw material **filament**, which are fed into an extrusion head. Filaments are typically made of **plastic**, but can include other materials such as **ceramics**.

During an FDM operation, the raw pellets or filament feeds continuously into the extrusion head, which quickly and carefully melts the raw material. The extrusion head then deposits the melted material through a nozzle, using pressure from the solid material being fed into it. The nozzle deposits thin layers of build material, often a **thermoplastic** such as **nylon**, layer by layer onto the build platform. If the part has overhanging components or other features that require **support structures**, some systems utilize a second nozzle to deposit different material. The FDM nozzles generally move horizontally while the build platform moves vertically after the deposit of each new layer. In some systems, nozzles move in three dimensions and are used to print curved layers. The plastic build layers fuse as they solidify to form a part.

When designing for FDM, engineers can adjust for changing variables of their build process, or even the physical part design itself. For example, if a vertical part wall is too thin, it may curve or bend before the plastic cools. Adding a **rib** to the part design can reinforce the wall. However, adding a rib also adds material to the part, and may impact production rates by increasing material costs or slowing build rates.

Similar to other **AM** methods, engineers or other designers designing for FDM use **software**, often **computer-aided design** (CAD), to create a 3D design file of a part. The CAD design file is a digital representation of the physical part, but FDM machines cannot directly read design files.

Because of this, an engineer or designer must convert the 3D design file into an **STL** file format, one of the most widely used file formats for 3D printing. The function of the STL is to encode the geometry of the 3D model into a sequence of interconnected triangles representing the external surface of the design. Digital **slicer** software takes the STL information and translates it into 2D layers used to physically build the part by the machine. Slicer software takes all of that information and converts it into **G Code**, a numerical language that controls the functions and motions of the FDM **hardware**. The G code program then moves the deposition head using **Cartesian coordinates**, a system that uses three **axes** to define the location of the nozzle, in order to accurately deposit the build materials.

FDM can work as an effective approach for a variety of manufacturing applications. Some industries have adopted FDM for mass production of end-use components and parts. Manufacturers may also use FDM to produce complex parts in **small batches** or for **mass customization**, which produces a large number of uniquely designed variations on a part.

Manufacturers in the automotive industry have integrated FDM technology into their production strategy in diverse ways. For example, FDM can be used to make specialized tools like a **fixture** to align windows in car doors during assembly. Other FDM applications may include mass producing end-use parts like brake **calipers**, or enabling customers to customize features that would otherwise be standardized when they purchase a vehicle.

Like the automobile industry, common FDM end-use applications for **aerospace** include fixtures and **jigs**. Other FDM applications include creating placeholder parts, which represent actual parts that will be installed at final assembly. The aerospace industry also utilizes the capabilities of FDM to produce complex shapes for **lightweighting**, which enables engineers to reduce the weight of the part without sacrificing quality. Lightweighting can take the form of replacing solid internal structures of parts with internal shapes that have a **honeycomb structure** or **lattice structure**. Lightweighting can also be accomplished by using a lighter **composite** material instead of a heavier material like metal.

FDM can also help manufacturers get consumer goods onto store shelves faster. Products such as jewelry, sporting goods, and consumer electronics can be printed in small batches with a shorter time from prototype to production. In some cases, consumer goods such as braces can be customized to a specific person.

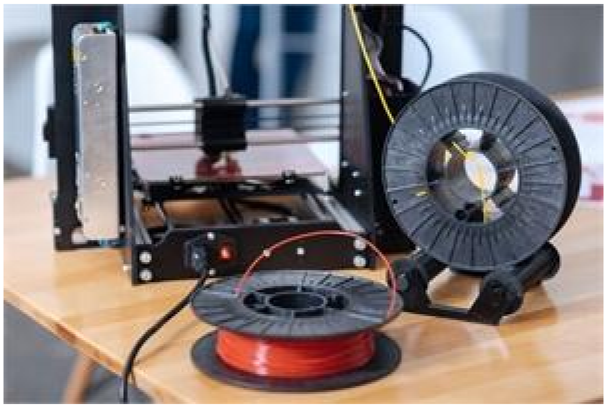
Outside of the manufacturing industry, additive manufacturing is commonly referred to as 3D printing. Desktop 3D printers are becoming more common in homes, schools, libraries, and other organizations outside of manufacturing. Since most desktop 3D printers use FDM, it is often used in training and education. FDM applications are especially useful in science, technology, engineering, and math (STEM) fields. For example, students in the classroom can learn to design and produce everything from simple bowls to robot parts.

FDM machines use a wide range of materials that can influence how an engineer designs a part. **Polymers**, which make up all plastics, are the most common materials used with FDM. The term **plastics** describes a group of commercial **synthetic** products that are **ductile**, not overly hard, and somewhat resistant to chemicals, heat, and **mechanical stress**.

Plastics fall into two broad categories based on the structure of the polymers that they are made from: **thermoplastics**, which can be repeatedly melted and re-shaped, and **thermosets**, which can only be melted and shaped once. Thermoplastics are popular with FDM because they can be reheated, cooled, and recycled with minimal impact on end-use performance.

Typically, these various types of FDM polymers are stored and dispensed through thin strands, or filaments, on a spool or through very small round balls of material referred to as **pellets**. Designers typically prefer using filament because of the material's consistent dimensions, which enable a machine to push an exact amount of material to the hot end of the extruder. In contrast, pellets may not hit the hot end of the extruder the same way every time, which could lead to inconsistent build patterns. Although harder to use, pellet systems can give FDM manufacturers of large 3D parts a cost advantage. A plastic filament can cost ten times more than pellets of the same weight, because of the costs associated with transforming the material into a filament and winding it on a spool.

Material Bin Holding Thermoplastic Pellets



Spool Holding Thermoplastic Filament

There are many different types of thermoplastic, thermoset, and other materials used in FDM. Each type of material has unique **physical properties** and **mechanical properties** that can affect many aspects of a part design.

Traditionally, **polylactic acid** (PLA) and **acrylonitrile butadiene styrene** (ABS) are the two most common thermoplastics used with FDM. PLA is often used in the food-packing industry to make containers or wrappers. Its popularity has grown because it is **biodegradable** and made from **renewable resources**. ABS exhibits excellent **toughness**, **thermal resistance**, and very low electrical conductivity. For this reason, AM manufacturers use ABS to build insulating parts for electric devices and systems, such as **electrical enclosures**.

Other thermoplastics commonly used with FDM include **polyamides** (PA), referred to as **nylon**, and **polyurethane**. Nylon has a high level of **wear resistance** and can gain strength when stretched, which makes it useful for clothing. Polyurethanes are also wear-resistant materials and have a variety of applications like hoses, tubes, and seals.

Thermoplastic **polyethylene** (PET), a type of **polyester**, is one of the most popular commercial plastics. PET's toughness makes it ideal for products like food containers and bottles. PET is also used to make **composites**, which are combinations of at least two materials, each from a different material group. Combining metal or **ceramic** with thermoplastics can make a lighter composite material that often works better than the individual materials on their own. For example, **carbon fiber** suspended in polyethylene can help make aerospace or automotive parts lighter, which in turn make a vehicle more fuel efficient.

FDM technology is constantly evolving and expanding to new materials. For example FDM can use **biomaterials** to fabricate living tissue for burn victims or ceramic material to create realistic dental implants.

An engineer or designer must consider several material factors when designing for FDM. A part's end use determines the ideal part material.

Every type of thermoplastic has its own temperature specifications, or **glass transition temperature**, when transitioning from a solid filament to a melted substance that can be extruded through the nozzle. Since melted plastic is soft when applied, it will generally cause some thermal distortion, which refers to changes in a part's shape due to heat. Thermal distortion can also cause holes to shrink or warp during the FDM process. Selecting the correct heat settings or adding a rib during the FDM process helps minimize issues associated with thermal distortion.

Another important material consideration in designing for FDM is layer adhesion, or the way build material layers stick together. For example, nylon filament is strong and versatile, but may have problems with layer adhesion. Cooler print temperatures may also affect layer adhesion, which can create areas of weakness or cause an end-use part to **delaminate**, or break into layers. Increasing print temperature in the machine or system settings may help create a stronger bond between the layers.

FDM designs that utilize lightweighting techniques, which maintain the strength of a solid part while reducing its weight, may use a honeycomb or **sparse fill** internal structure. A sparse-filled internal design uses geometry to create a lattice-type structure that acts like a series of internal support structures with holes in between. Sparse-fill design only affects the interior of a part. This means that even though an FDM part may look different on the inside, the outside of the part looks and functions the same as a solid part. This enables manufacturers to use the same post-processing techniques for end-use production, like sanding and painting, that they would use on a solid object. Using sparse-fill techniques may reduce material costs. However, solid parts may use less support material and reduce production time.

Designers must also exercise caution in cases where an FDM part will be used in living tissue, such as a medical or dental implant, or as **personal protective equipment** (PPE) that touches skin. For these parts, the build material must be **biocompatible**, or free of toxic chemicals or harmful additives.

How materials and machines are stored can affect the FDM process. All thermoplastic materials have the potential for **creep**, which refers to the deformation of a material that occurs from long-term stress or strain. Most materials are not loaded in a machine long enough for creep to occur. However, if a situation occurs where a machine holds a load for an extended period of time, creep may affect the build material. Creep can affect end-use parts subjected to constant bending stress. In order to minimize issues with creep, designers may choose a plastic like ABS or nylon that has higher creep resistance.

Some common part structures may cause issues in FDM part designs.

A **bridge structure**, which is a horizontal part feature that extends between vertical features, is one common part structure that may pose problems. For example, if a bridge structure on an FDM part is too long between **anchor points**, the material may sag. To avoid sagging, an engineer might consider including more anchor points to shorten the length of bridges between them.

Because shrinkage may occur, holes in FDM parts may not be the correct size. For holes with precise **tolerances**, engineers may design the hole slightly smaller than required. Machinists can then cut the hole to an accurate size with traditional machining processes such as drilling. Print orientation may also represent a design solution for problems associated with holes. Horizontally printed holes generally create stronger hole structures. However, vertically printed holes work better for overall accuracy and drilling.

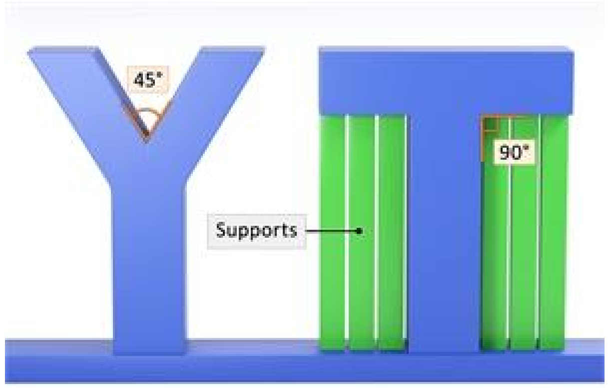
In other instances, the curve of a hole may not come out perfectly round because of **compression** issues with the FDM layering process. When the FDM nozzle layers the material, the force of it pressing down may likely cause the hole to build smaller than intended. Instead of a circular hole, an FDM designer might choose a teardrop shape, which disperses pressure differently and avoids a large overhang. Teardrop hole designs may prove particularly useful with horizontal holes, in order to prevent the top of the circle from sagging.

Threads, both internal and external, may also create design issues for an FDM **mating part**. For instance, rounded thread edges may work better than sharp edges, which are more likely to break under stress. A pilot point, or dog point thread, is another design solution to external thread issues. Because pilot point threads have a rounded tip that extends past the thread, it may make the thread easier to print. Instead of internal threads, some FDM designs may choose to use fastening **hardware**, like **locknuts** or **embedded nuts**, because they reduce the risk of stress and cracking in the part.

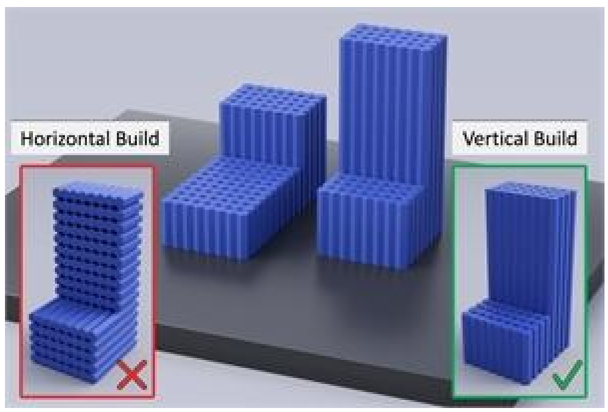
FDM processes can achieve great **part complexity**. Part of a successful FDM design strategy considers the factors which influence part shape and strength. A more complex part will likely need a support structure during the build process.

Support structures act as scaffolding while an FDM machine builds a part layer by layer. The number of support structures a part needs depends on its size and shape. For example, a T-shaped part feature includes two ninety-degree vertical overhangs, which need supports to print properly. Orientating the part design in different ways, such as horizontal, may reduce the amount of support structures needed. However, not all overhangs require support structures. If a vertical overhang has an angle of 45° or less, like a Y-shape, it can print successfully without support structures. This is generally referred to as the 45° rule in FDM design. In end-use production, designing a part with features of 45° or less may save material cost and production time.

The strength between material layers can impact the strength of the part structure. Generally, the strength between part layers is weaker than the material within the layers. Proper design techniques, like the orientation of the build process can offset the weak areas of a part by minimizing separation points. For example, changing the direction of the way a part is layered may increase its resistance to impacts. Also, minimizing severe **deflection** points in a design can make a finished part stronger. Deflection refers to the degree of change that occurs in a part structure when a force is applied.



Design Factors for Support Structures



Minimizing Separation Points

Since FDM machines create parts in thin layers, small ridges will remain on the finished part surface. In addition, removing support structures by **mechanical** or **chemical** means may leave blemishes or imperfections. Manufacturers must therefore take finishing and **post-processing** into account when designing for FDM. Common post-processing for FDM parts includes **abrasive finishing** and **burnishing**, both of which create a smooth and more attractive surface. Painting and **sealing** are common processes that apply coatings to parts, as does **plating**, which adds a thin layer of material to the surface. Applying coatings to an FDM part improves its appearance and can also protect it from exposure to chemicals or other environmental factors.

Designers for FDM must consider how post-processing will affect a part, including the amount of material it may add or remove, and the effects of heat from finishing processes on the plastic. For example, abrasive finishing processes remove material, so the designer may need to design a part slightly larger than necessary, while coating processes add material and thus add to part size. Engineers must also consider aesthetics when selecting a type of **grit**, or other similar abrasive material for FDM part design. For example, a grit that is suitable for PLA may not create the same smooth surface for another material.

Abrasive Finishing

Painting Plastic Elements

302: Design for Material jetting

Material Jetting, also known as **PolyJetting**, is one technique in a larger group of building methods referred to as **additive manufacturing** (AM) or **3D printing**.

A benefit of material jetting is its ability to deposit multiple types of material in a single print run to create realistic-looking objects. For example, material jetting can use multiple materials to build a single part or multiple separate parts on one build tray. The material jetting process can also blend **raw materials** to digitally create a **digital material** with specific qualities like color or hybrid properties like rigidity and toughness.

Although each AM method requires specific equipment to build parts, they all share the same basic five steps of the **design for additive manufacturing** (DFAM) process: **conceptualization**, **planning**, **design**, **testing**, and **production**. The flexibility of material jetting and other AM methods enables engineers and other designers to consider things like part functionality, complexity, and customization when designing for AM. The planning, designing, and testing steps also offer AM designers opportunities to increase production efficiency, since creating a **prototype** does not require additional tooling or machine configurations.

The material jetting process works much like traditional **two-dimensional** (2D) inkjet printers. However, instead of printing droplets of ink onto paper, material jetting dispenses droplets of build material onto a build platform to create a **3D** part layer by layer. During the material jetting process, one or more **print heads** generally move horizontally to dispense a layer of material, while the build platform moves down vertically after the deposit of each new layer. Most material jetting processes use **photopolymers**, which only solidify under **ultraviolet** (UV) light. Because of this, most material jetting print heads have a UV lamp to **flash cure** the material after deposition.

Material jetting is considered one of the most accurate of the **AM** methods. A material jetting printhead may contain hundreds of individually controlled drop-on-demand nozzles, which dispense very tiny drops of material as small as 16 **microns**, or about .00063 of an inch, in thin layers to build a part. This enables the curing process to occur almost immediately when exposed to UV light. **Wax**, another common material used with material jetting, does not require UV curing.

The build materials used in material jetting processes can vary. However, most material jetting materials fall into two general categories: photopolymers and waxes.

Material jetting often uses a liquid-like form of **thermoset** resin called a photopolymer, which permanently hardens when exposed to **UV** light. Because of a photopolymer's sensitivity to light, the material may weaken faster over time compared to typical plastics. The fluid nature of photopolymers enables them to flow easily through the printhead nozzle as tiny droplets almost as small as a human blood cell. The droplets' small size allows the machine to deposit them very precisely on the build platform.

Most photopolymer types used for material jetting are **proprietary**, or made specifically for a certain company's machine. These photopolymers are designed to imitate popular plastics, such as **acrylonitrile-butadiene-styrene** (ABS) or **polypropylene** (PP).

The term wax refers to a variety of organic substances characterized by their high **malleability** and low **melting point**. In material jetting processes, waxes are typically made water **soluble** for easy removal. In material jetting, designers may use wax to create **support materials** and **matte** surfaces. Material jetting can also use wax for printing disposable or **sacrificial patterns** for **investment casting**.

The ability to create inexpensive wax patterns and molds with material jetting can enable manufacturers to **rapid prototype** or create many prototypes in a short time. As a result, manufacturers can test and evaluate many designs and identify any possible design issues before going into a full production run. This may reduce the risk of a final part not working as expected.

Typically, a material jetting machine builds parts from raw plastic materials referred to as **resins**. Unblended resins are called **base** resins, which fall into four general categories: **rigid**, **transparent**, rubber-like, and customizable.

Designers use resins in the rigid family to create stiff, precise objects such as precision tools, assembly **fixtures**, and prototypes that need detailed features. Designers can also use rigid resins to replicate the look and functionality of traditionally manufactured parts. For example, a material jetting machine can create a **functional prototype** of a product like a hard hat and other **personal protective equipment** (PPE). Functional prototypes enable a designer to conduct performance tests before final production.

Rubber-like materials can enhance the designs of rigid parts. For example, a designer can add a rubber-like hand grip to an electric drill to make it nonslip. Manufacturers can also create near-perfect prototypes of rubber parts for testing and **iteration**, which is the process of creating multiple versions of a prototype to improve design. For example, a manufacturer may want to test multiple versions of an electrical junction box to determine how it reacts to extreme weather changes.

Transparent and **translucent** materials can be combined with rigid and rubber-like materials to create products that have clear parts, such as safety glasses and other eyewear. Designers can also use transparent materials to imitate the appearance of glass bottles or create other clear packaging.

Many projects may require designers to customize their materials for a particular function. For example, medical devices and instruments, such as **forceps**, require material that is biocompatible. Other parts built with material jetting may need high temperature resistance. For instance, heat-resistant materials are necessary for testing hot air or water flow in pipes.

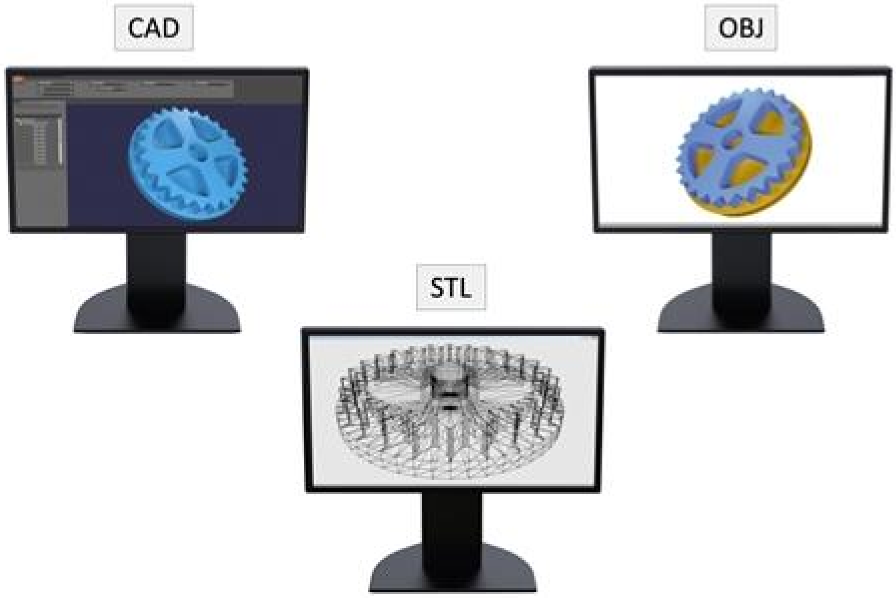
Print heads on material jetting machines have multiple **nozzles** that can deposit different types of materials during the same print job. This ability to control multiple nozzles gives designers the ability to **modulate**, or adjust, the types of material used to build a part. Three common material jetting modulation types include gradation, blended resin, and mixed tray

Gradation enables a designer to use multiple materials at different places in the same part. This allows designers to adjust material properties or colors in specific areas of the part. A chief benefit of material jetting is that it can combine multiple materials to create a single part within the same print job, referred to as a **mixed part**. For example, an engineer can design the casing of a **hand drill** with a tough, durable **plastic** to absorb vibration, and combine it in the same process with a slip-resistant rubber-like material for the hand grip area.

The ability to control multiple nozzles at once also enables designers to **blend** different build materials in their raw form, or resin state. The result of this blending creates a composite, or **digital material**, which gives a designer control over a parts rigidity, softness, and color. For instance, from only three primary colors, material jetting designers can create thousands of different shades of color. This enables designers to create a functional prototype with the intended color and surface finish without extensive post-processing.

Designers can also create multiple parts with different materials in a single tray, referred to as a **mixed tray**. This enables a designer to create separate objects, like a blue rigid plastic container and soft rubbery sole of a sneaker, during the same build. Mixed tray printing can also enable multiple designers to print their parts at the same time, leading to quicker turnaround times for prototypes and other parts.

Like other AM methods, designers for material jetting use **software**, often **computer-assisted design** (CAD), to create a 3D design file of a part. The CAD design file is a digital representation of the physical part, but material jetting machines cannot directly read design files.



Because of this, a designer must convert the 3D design file into an **STL** file format. The STL software converts the geometry of the 3D model into a sequence of interconnected triangles representing the external surface of the design. If a part has a different material in a certain area of the part, then a designer must create a separate STL file for each area. If a part has blended materials, then a designer may also need to create a **VRML** file or an **OBJ** file, either of which communicates characteristics like color and surface quality to the machine.

Next, digital **slicer** software translates the STL, VRML, and OBJ information into digital versions of the 2D layers that the machine will deposit to physically build the part. The digital slicer software then converts the 2D layer information into **G Code**, a numerical programming language that controls the functions and motions of machine tools like material jetting machines. Essentially, digital slicer software breaks a digital model into the layers of material that the material jetting machine will deposit and bind, while the G code program directs the print head movement back and forth across the build platform.

Material jetting machines typically have two options to consider for surface settings, or modes, when printing an object: **glossy** or **matte**.

Matte Surface

In the matte setting, a material jetting machine will cover the entire part with a thin layer of support material, regardless of structural requirements. The process of surrounding the part with support material creates a uniform matte surface across the entire part. Typically, matte surfaces have a rough, textured appearance compared to smooth glossy finishes. Matte surfaces require more material and more post-processing, which typically makes matte surfaces more costly to produce.

Glossy Surface

Designers use the glossy setting to create a sleek, shiny object surface. Unlike the matte setting, glossy surfaces only use support material when a structure requires it, because support material may damage the part when removed. Typically, material jetting machines cannot print glossy surfaces underneath support material, which makes it extremely difficult to produce a uniform surface. To avoid this issue, designers may limit or avoid using support structures for parts with glossy finishes.

Designers may also print a part in multiple pieces for later assembly, which reduces the need for structural support material with both glossy and matte settings.

Material jetting has a well-earned reputation for creatin realistic-looking prototypes. However, the brittleness and low **ductility** of material jetted parts makes them less optimal for **end-use** production. In addition, photopolymers used in the material jetting process typically have a high **degradation rate**, which means that they break down relatively quickly when compared to other plastics. For photopolymers, using the correct UV light setting is crucial. Low UV intensity during the curing process may not fully solidify the part, which can cause sagging or a wavy surface texture. Checking the UV light before each build may help avoid this issue.

The importance of **part orientation**, or the position of the part as it is built, is typically reduced with material jetting. Because of the fine layering of material jetting, it reduces the likelihood that certain building positions will reveal layer lines. AM machines can build parts in a variety of different positions, all of which can affect their final quality. For example, building a part facing upward helps protect against potential defects during printing. Even in material jetting, designers must consider the orientation of any holes that may appear in a part. An incorrect support material setting on a machine may sometimes cause a matte surface to appear around holes or other openings when printing a glossy surface.

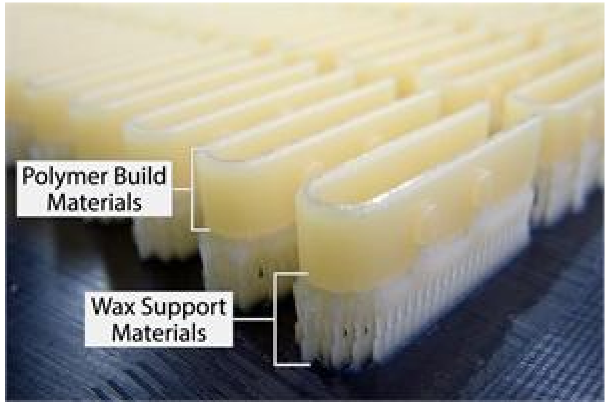
Part Sagging

Matte surface appearing around holes.

Material jetting processes typically use the same wax material to create a matte finish as they do to form support structures, which provide reinforcement for a part during the build. Regardless of the part orientation, material jetted parts need support structures for any overhangs or under-supported sections. However, as a general design rule, limiting the need for support structures in a part can help reduce the costs associated with support material.

Material jetting support material typically comes in three categories, based on the way material jetting machine operators remove the material after printing. Operators can remove the first category of support material by hand or water pressure. A second, less popular category requires an operator to use a **caustic** chemical solution to dissolve the support material. This method helps provide a smoother part surface, but the required chemicals are harmful to employees and the environment. A third category of support material is completely **water-soluble**, which makes it optimal for parts with fine features. However, water-soluble support structures can only work with certain machines and base materials, which typically makes it the least used of the three options.

Courtesy of Stratasys.

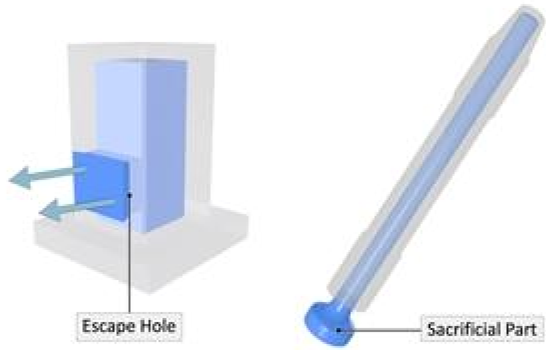


Material Jetting Part and Support Material

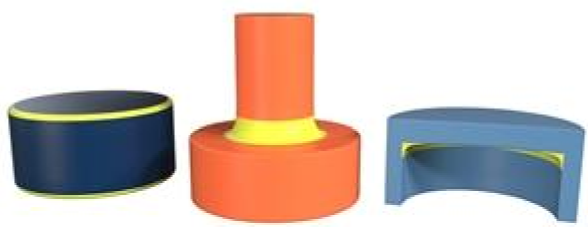
Internal structures can present unique challenges when building with material jetting. For example, holes or other hollow part features may sag or distort during a part build. Part designs with hollow features therefore typically require plans to fill the empty space with support material during the build process. Removing this material from the completed part may be difficult, especially with small or extended hollow spaces. Because of this, a designer may add an **escape hole** to the part to make support material removal faster and easier. If an escape hole isn't feasible, a designer might extend the support material outside of the part for easier hand removal.

Designers must also consider the thickness of any walls that surround a hollow feature. Thinner part walls may deform or break under stress, especially in **joint** areas where material sections meet. To help provide more strength and stability, designers can add a **fillet**, or rounded corner, to reinforce part joints.

When designing for material jetting, engineers can adjust for changing variables of their build process, or even the physical part design itself. For example, if the part has overhanging components a print head may deposit wax as a support structure. Adding a rib or boss to the part design can help strengthen the wall of a part. However, material jetting build materials are generally more expensive compared to other AM technologies, so adding material may impact production rates by increasing material costs.



Design Solutions for Hollow Part Features



Fillet Examples

Courtesy of Stratasys.

After printing, a material jetted part will typically need additional post-processing or finishing, which is a group of procedures used to clean, improve, or create an attractive surface finish on a part. Support material must generally be removed, which requires specific techniques to avoid damaging any delicate part features. For example, removing support material using water pressure requires a special chamber with operators wearing additional **PPE**. Before removing support structures with a caustic chemical solution, an operator will need to prepare a cleaning tank with the proper chemical ratios. Soaking a part in caustic chemicals might take hours. Because of this, operators may try to remove as much material as possible by hand before soaking to speed up the chemical removal process. For larger part runs, an operator may soak the parts in batches.

Post-processing can improve surface finish and remove blemishes or imperfections that may have occurred during the material jetting process. Because post-processing may add or remove material to a part, designers must factor it into their part design. For example, if a part needs sanding, a material jetting designer should build the part a little larger to account for the removed material. In other instances, some designers might apply a coat of clear paint to a transparent surface to give it a more vibrant finish. Instead of painting, operators may add a **glycerol** coating to strengthen parts and better protect them against environmental factors.

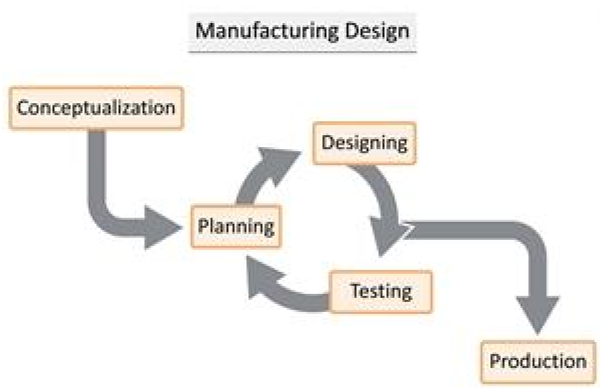
303: Design for Directed Energy Deposition

Designing products for **additive manufacturing** (AM) requires the same basic processes used in **traditional manufacturing**. A traditional **design for manufacturing** (DFM) process follows five basic steps: **conceptualization**, **planning**, **designing**, **testing**, and **production**. While each step has various restrictions, **design for additive manufacturing** (DFAM) allows designers to approach each step without the same constraints of traditional DFM.

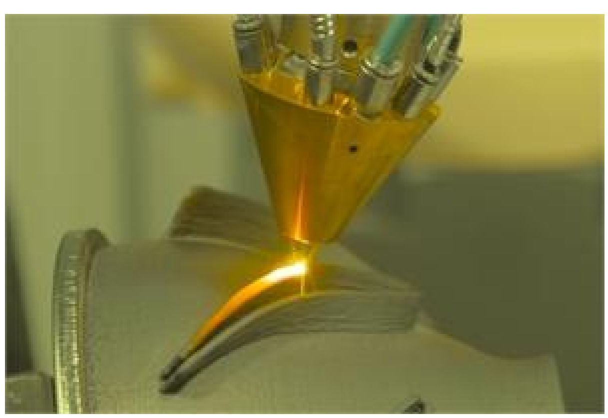
One type of AM process, **directed energy deposition** (DED), uses intense heat from a **thermal energy source** to melt **powdered metal** or metal wire **feedstock** to build layers of metal. DED can optimize DFAM in different ways. For example, standard DED requires fewer programming tasks than traditional machining, which requires complex part programs to accurately create part features throughout the cutting process. Additionally, standard DED requires less machine setup than traditional manufacturing when building parts from the ground up, which can help optimize the testing and production phases of DFAM.

DED tools may use a **laser**, **electric arc**, **plasma arc**, or **electron beam** as a thermal energy source. Design considerations can vary based on the heat source and the materials used in each method.

This material is based upon research supported by, or in part by, the U.S. Office of Naval Research under award number N00014-18-1-2881 led by the National Center for Defense Manufacturing and Machining (NCDMM).



5 Steps of DFM and DFAM



Directed Energy Deposition

Similar to other traditional manufacturing and **AM** methods, design for **DED** begins with creating a **computer-aided design** (CAD) model. CAD models, which start as 2D sketches or 3D designs, are digital representations that contain the geometry of all part features and specifications for raw materials that make up the part. Once complete, the CAD model is exported as an **STL** file, which converts the CAD model into a series of interconnected triangles. Then, a **slicer** program "slices" the STL file into layers, converts the layers into toolpaths, and exports the converted file as a **G code** file. Technicians may adjust deposition width, temperature, and other parameters in the software, which adjusts the G code file based on these settings. The G code file is then exported and uploaded to a machine tool equipped for DED, and controls the material's deposition.

Standard DED processes apply raw materials in the locations that the G code program specifies, while using a thermal energy source to melt the raw material and fuse it into layers. Different DED methods use different types of material feedstock and different heat sources. For example, **laser metal deposition** (LMD), the most common DED method, dispenses powdered metal from one or more **material hoppers** and melts the powder into layers using a laser.

There are three main types of DED. Each process has a different heat, or thermal energy, source used with specific feedstock types, which create strengths and limitations that AM designers must consider.

Laser metal deposition can print parts at higher resolutions than other DED methods and can be easily used in hybrid machining centers. Since **LMD** typically uses only powder, it also has a smaller **deposition width** and prints slower than other DED methods. LMD inputs the lowest amount of heat into the **substrate**, which results in a fine-grained microstructure. This means LMD has the highest quality metal deposition. LMD is well-suited for building and repairing parts using specialized metal alloys and **metal matrix composites** (MMCs). It is also best for repairing surfaces that may be difficult to reach, or building high-performance parts that require more precise dimensions. LMD can also be used to print large parts but deposits slower than wire methods, and powder feedstock is more expensive.

Wire arc additive manufacturing uses the same technology as traditional welding processes. WAAM has a larger deposition width than LMD since it most often uses wire feedstock instead of powder. This makes it suitable for building larger parts of low to medium complexity as it operates at a higher speed and lower cost than powder DED methods. WAAM is ideal for repair applications, and it is often used to produce large parts for **forging**, or non-forged parts that undergo low to moderate impact stress during use. However, WAAM parts print at lower resolutions and may experience more **residual stress** from thermal energy than other DED methods, which can alter material properties that affect part quality and durability. For this reason, WAAM is not typically used for high-performance parts that undergo heavy use stresses.

Similar to WAAM, **electron beam freeform fabrication**, a technology first developed by **NASA**, uses wire feedstock and is ideal for building large parts that are traditionally produced using subtractive machining methods. Sciaky Inc. commercialized the technology as **electron beam additive manufacturing** (EBAM). EBAM uses an electron beam gun instead of a welding torch or laser. The high melting efficiency of the electron beam enables it to deposit wider beads at a time, which produces faster build rates than other DED methods. EBAM can build large, high-performance parts with medium complexity more effectively than WAAM and at lower cost than LMD. EBAM technology has been used to build high-performance aerospace and satellite components. However, EBAM requires a sealed vacuum chamber to prevent gases or air particles from altering the properties and function of the electron beam. This makes it the more challenging to integrate EBAM with other processes or implement in hybrid machining centers than other DED methods.

DED allows designers to easily build with multiple metals and even combine metals as alloys during the build process. This allows part designers more freedom when determining a part's material composition in **CAD**. However, different DED applications require different DFAM considerations.

DED is most often used to repair worn or damaged parts. Instead of using CAD to create a digital model, repair technicians typically scan or probe the damaged part while it is on the machine. This requires a technician to first machine away the part damage to a known dimension, then probe the part again to update the model. Next, the technician uses specialized software integrated with the probe and machine tool that can translate the digital model into a G code program with precise toolpaths. A technician runs the program, and the DED tool builds up the damaged part to dimensions slightly larger than the part's final size. Finally, the repaired portion of the part is machined down to its final size and surface finish. Final machining is often done as a separate post process but can be streamlined on a **hybrid machining center** equipped for DED.

Building new part **features** and adding material **coatings** directly onto existing parts are also common applications for DED. The feature addition process is similar to standard DED part production. Technicians use a CAD model and slicing software to create a G code program with toolpaths to build one or more features onto the part base. Part designers often leverage DED to create new features made of different metals, such as adding aluminum alloy flanges onto a steel component to improve thermal conductivity.

DED material coating processes, often called **laser cladding**, typically do not require a CAD model. Instead, technicians may scan or probe the part, similar to a repair process. The tool then applies coatings of different metals in order to improve various **properties** such as wear, heat, or impact resistance, which improve the durability of the part.

DED can also build **near-net shape** parts and is especially suited for building curved parts such as **rocket nozzles** and other aerospace components. DED tools are often equipped to apply different metals from multiple **feedstocks**. This allows manufacturers to produce a complete part that contains multiple metals in a single build. A near-net shape part containing multiple metals must properly incorporate each metal into the CAD design. Then, a G code part program must be able to control the deposition of each metal in the appropriate areas according to the CAD model.

Different machine tools may be used for directed energy deposition. Machine controls for each tool can influence the design process in specific ways.

The most standard DED machine tools are standalone DED machines. Standard DED machines may use **three-axis**, **four-axis**, or **five-axis** movement to control deposition. Three-axis machines allow vertical tool movement in the Z axis and lateral tool movements in the X and Y axes. Four- and five-axis machines allow rotation of the workpiece in one or two rotational axes, which allows for more complex part design. Standard machines include laser metal deposition (LMD) and wire arc additive manufacturing (**WAAM**), which is similar to traditional welding. Also common is electron beam freeform fabrication, a technology first developed by NASA which uses an electron beam gun and wire feedstock to fabricate and repair aerospace parts in space. Sciaky Inc adopted the technology for their electron beam additive manufacturing (**EBAM**) machines, which also use wire feedstock.

Robotic arms are also commonly used for DED. In this machine tool setup, a DED tool and feedstock for LMD, WAAM, or EBAM is mounted as an **end effector** on the robotic arm. Robotic arms typically move along multiple axes. **Multi-axis** movement includes both linear and rotational movements. Moving in multiple axes allows the DED tool to deposit material from more angles than a standard three-axis DED machine, which allows the machine to create more complex parts.

Hybrid manufacturing machines can greatly improve design flexibility for DED. Machine controls using DED and cutting tools on a hybrid machining center are similar to controls on traditional **CNC mills**. While some CNC mill controls use three-axis machining, more advanced controls use five axis machining. Equipping DED tools alongside traditional machining tools in a single tool changer allows unique design capabilities, such as finishing internal surfaces before they become obstructed by other parts of the build. Designers improve precision and accuracy while constructing the build rather than using a separate finishing process after the build is complete.

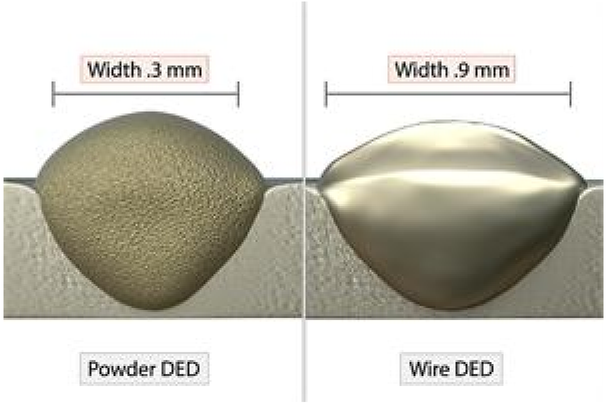
DED typically creates parts from powdered metal or metal wire and is considered a metal **AM** process. An understanding of **metallurgy** is important when designing metal parts for DED, especially when designing parts that contain multiple metals. Metals have different properties and may behave differently when in contact with other metals. For example, using aluminum in contact with copper can cause corrosion due to differences in the chemical properties of both metals. Designers must also consider environmental factors. Since metals also behave differently within certain temperature ranges, the properties and dimensions of a part containing multiple metals, such as a steel part with an aluminum flange, will not change in the same way as it cools.

Part designers must also consider the type of metal feedstock that a DED process will use. Powdered metal feedstock can print parts at a higher **resolution** than wire feedstock. Some deposition heads can dispense metal powder from two hoppers at once, allowing the deposition head to fuse two types of metal together into **metal alloys** when building a single layer. Powdered metal also creates less waste than wire feedstock. Powdered metal feedstock is ideal for building parts using high performance metals and **metal matrix composites** (MMCs).

Although metal wire feedstock creates lower surface resolution than powder, there is typically an **inverse relationship** between surface resolution and build rate for AM parts. This means metal wire DED can create parts at faster **build rates**. Due to greater deposition widths that allow faster build rates, as well as the lower cost of wire feedstock, wire DED methods are typically preferred over powder methods for building very large parts.

Multiple aspects of the DED build process, such as the size of the feedstock and the type of thermal energy used, produce varied results in the final part. Temperature and other machine parameters affect final part properties like **build resolution** and **deposition width** in various ways. Build resolution measures the thickness of the part's layers, while deposition width is the width of each layer deposited during the part build. DED machine operators adjust width and layer thickness settings based on the desired build resolution of the completed part. A high build resolution or narrow deposition width means that the layers are smaller, which results in a more refined appearance but also a slower build rate.

Along with build resolution, part designers also choose specific materials for certain part components. Machine operators often must adjust machine settings based on the build material. Overall, lower build temperatures result in higher-quality parts, but the appropriate temperature range varies based on material type. Heat and **shrinkage** can alter the **microstructure** of materials in various ways and can produce poor quality parts if not controlled properly. Most machines adjust temperature automatically based on the material type selected by the operator. However, designers and engineers must understand how temperature changes will influence certain properties in different materials and how to make adjustments when needed. Build parameters must also be adjusted in order to carefully balance the quality of the finished part with speed and efficiency during the build process.

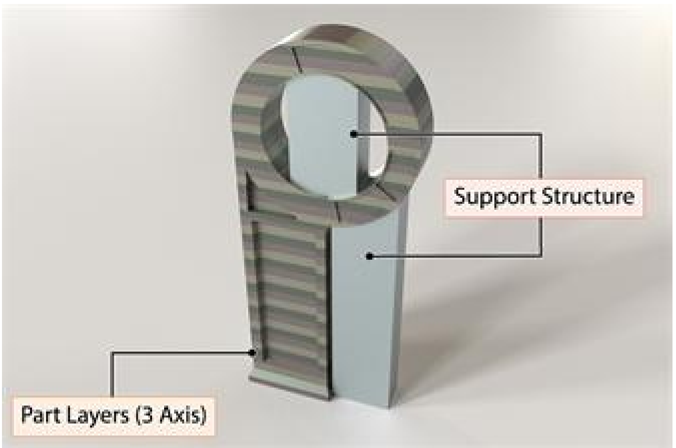


Deposition Width

Along with build parameters, designers must also consider the effect of layer slicing methods on part dimensions and surface finish.

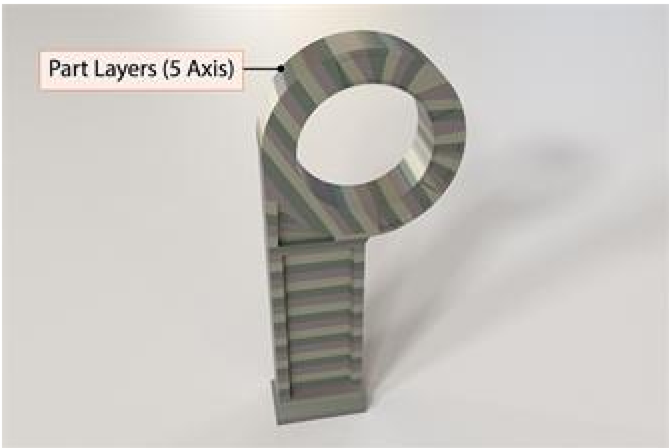
Simple shapes with squared features can be built efficiently with **uniform slicing**, which deposits each layer at a uniform thickness. However, curves and other more complex shapes may require **adaptive slicing**. Adaptive slicing prints thinner layers for curved areas on a part, and thicker layers for straight or squared features. Printing thinner layers produces smoother curved shapes than thicker layers but increases build time. Adaptive slicing still allows faster printing for straight areas on the part.

Manufacturers typically use **post-processing** to smooth out the layers to complete the shape to specifications. However, adaptive slicing can be used to build smoother curved shapes on parts if post-processing is not possible, or to reduce the amount of material that must be removed during post-processing.



Three-axis requires support for overhangs.

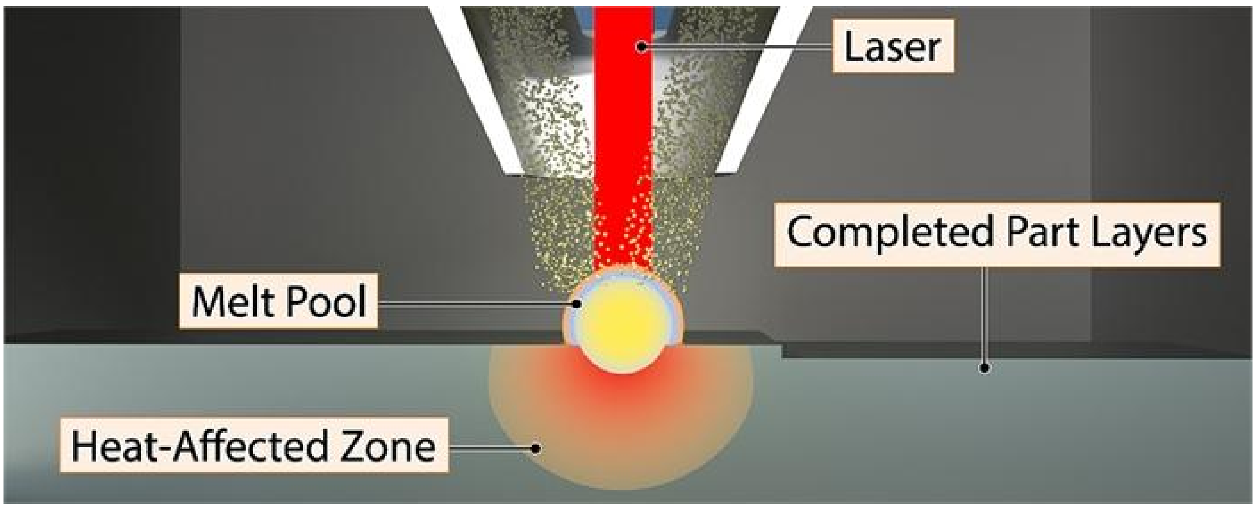
Some standard DED machines use three-axis movement. Deposition heads on three-axis machines move along three linear axes and can print curved shapes and **overhanging features** up to a 45-degree angle. Similar to parts made with other AM methods like **fusion deposition modeling** (FDM), overhangs greater than 45 degrees require **support structures** since the weight of these features will fall or droop without support from beneath. However, DED typically does not use support structures due to the difficulty of removing the metal and the metal waste it creates.



Multi-axis prints some overhangs without support.

Advanced DED tools that use four- or five-axis movement, greatly enhance DED design capabilities. Five-axis movement includes the three linear axes and allows the worktable to turn along two additional rotational axes. By tilting the bed, a five-axis machine can print overhangs greater than 45 degrees without requiring support structures. However, using DED on a five-axis machine requires advanced **slicer** and **computer-aided manufacturing** (CAM) software to calculate the angle of the bed and the appropriate angle for printing part layers.

In addition to DED materials and methods, AM part designers and technicians must also account for various DED operating conditions that can affect the properties of the finished part.



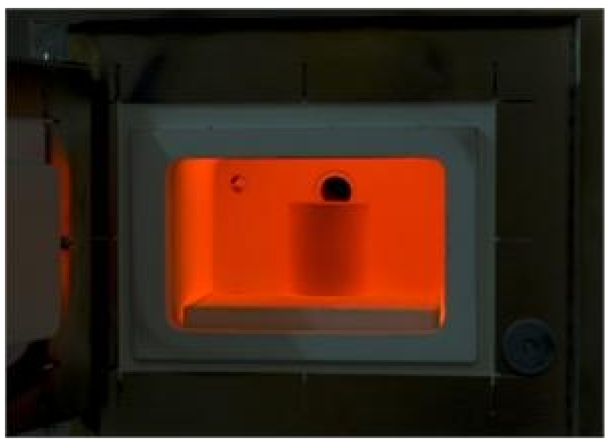
DED requires an intense amount of heat for a laser, electron beam, or arc to melt the metal during a build. Similar to welding, parts created with DED will have a **heat-affected zone** (HAZ). The HAZ is the area just outside of where the new layer is melted and fused onto the part. In DED, the heat affected zone occurs in the area around the **melt pool**, meaning it extends along each layer of the part. Understanding the heat-affected zone is important because extreme temperatures can cause thermal and residual stresses that affect the **mechanical properties** of different types of metals in different ways. Similarly, designers must understand and account for the cooling rates of metals, as well as how their properties change as they solidify into layers.

Environmental factors, such as room temperature, can also affect the quality of finished parts. Most DED processes, particularly WAAM, require a sealed vacuum or inert gas chamber, or require a **shielding gas**, such as **argon**, to prevent oxidation, contamination, and the influence of outside temperatures. The chamber or shielding gas ensures that the mechanical properties of the dispensed metal are not disrupted by the surrounding environment.

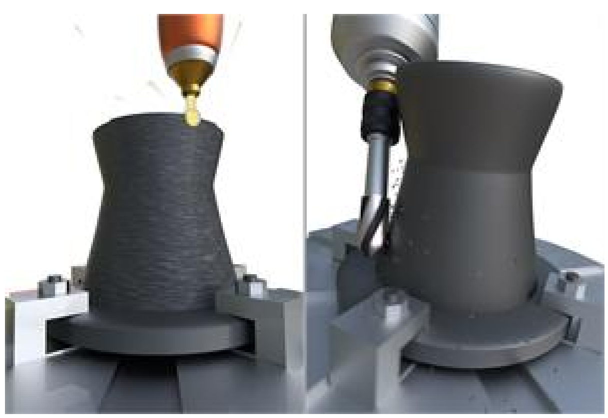
Post-processing is generally required for any part created using AM, but methods may vary depending on the AM processes. Since DED uses intense heat to melt the metal feedstock, post processing may include **heat treatment** to improve material properties like hardness, which helps to ensure quality and durability. Heat treatment processes can also help prevent damage caused by residual stresses in the heat-affected zones that can potentially lead to part failure.

Like all AM methods, DED cannot produce holes and threads with the same precision or produce the same surface quality as **subtractive manufacturing** methods. Finished parts with tight tolerances are often required by customers purchasing the **end-use** products. Abrasive finishing processes like **grinding**, **sanding**, or polishing are typically a requirement of DFAM.

DED is commonly used in hybrid manufacturing applications. Cutting tools on a hybrid machine allow finishing, threading, and other subtractive processes to be completed in a single process rather than separately, reducing production times. However, parts produced with hybrid DED may still require heat treatment, **shot peening**, or other post-processing methods to control material properties and ensure part quality.



Heat Treatment



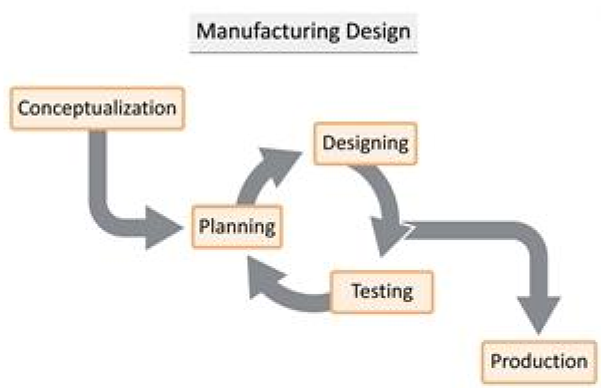
DED and Finishing on a Hybrid Machine

304: Design for Laser Powder Bed Fusion

Parts produced by **additive manufacturing** (AM) go through the same five basic steps as traditionally manufactured parts: **conceptualization**, **planning**, **designing**, **testing**, and **production**. **Design for manufacturing** (DFM) is a method that can help manufacturers optimize each step in a variety of ways. **Design for additive manufacturing** (DFAM) is a specific type of DFM used for AM processes, such as **powder bed fusion** (PBF).

Laser powder bed fusion (L-PBF), the most common PBF method, uses a laser beam to heat layers of powdered material in order to build a part. L-PBF manufacturing requires knowledge of and ability to use software, as well as an understanding of machine settings, parameters, and operating conditions. Part designers use **computer-aided design** (CAD) and **generative design** software to conceptualize parts and define part dimensions, determine material composition, and establish part quality requirements. L-PBF machine operators use specialized software on L-PBF machine **interfaces** to set machine operating parameters and run the L-PBF production process. Design for L-PBF allows part designers to enhance design concepts, improve part functionality, increase cost savings, and reap other benefits when compared to traditional DFM processes.

This material is based upon research supported by, or in part by, the U.S. Office of Naval Research under award number N00014-18-1-2881 led by the National Center for Defense Manufacturing and Machining (NCDMM).



Digital tools for **L-PBF** include **CAD** software for design and specialized software for running the production process.

In order to produce a part with L-PBF, a design engineer typically creates a 3D model of the part using CAD software. CAD software ranges from free software for basic design to more expensive software with more advanced design capabilities. Once the CAD model is complete, it is converted into **stereolithography** (STL) file format. While some **AM** methods translate the STL file into a traditional **G code** file, L-PBF uses specialized **build processor** software to produce a different file type. The build processor software, which is usually specific to the machine, converts the STL file into a **job file** that the L-PBF machine can read. The job file controls the laser temperature, the laser path, the powder application, and the movement of the machine based on the part geometry, material types, and machine settings.

Before the L-PBF production process can begin, the **powder bed** must be filled with powder and loaded onto the L-PBF machine. Most machines then feed the powder upward from the bed into the **build chamber**. The powder is fed in specific quantities to form each layer, and the **powder blade** spreads each new powder layer out on the **build platform**.

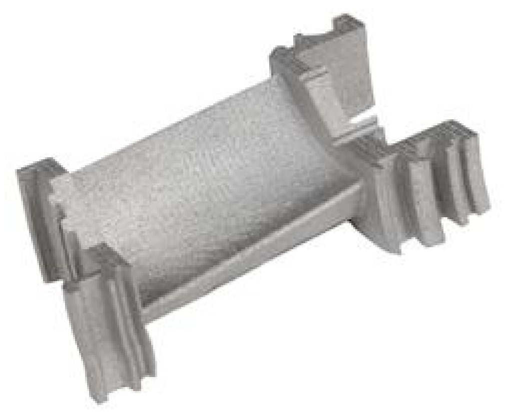
The **laser beam** is emitted through a lens to fuse or melt precise areas of each layer of powder. The specific temperature of the laser depends on the type of material. The path of the laser is controlled by specialized software in the L-PBF machine to fuse or melt areas of each powder layer based on part dimensions specified in the original CAD model of the part.

As each layer of the part is completed, the build platform lowers the part deeper into the build chamber. The part grows until it is fully submerged in the unused powder in the build chamber. Once the entire part is complete, the part is typically raised to the top of the build chamber and removed by an operator. On some machines, the powder bed is removed first, and the powder is then emptied out before the completed part is removed.

Laser powder bed fusion processes can use a wide range of materials, including **polymers**, **ceramics**, and metals. Powdered metal is the most common type of material used in L-PBF applications and is available in a much wider selection than polymers or ceramics. Metals are strong and have the highest electrical and **thermal conductivity**. L-PBF make parts from pure metals, **metal alloys**, and **metal matrix composites** (MMCs). Producing metal parts with L-PBF allows for greater design possibilities than machining since cutting tools provide less flexibility than building a part from scratch.

L-PBF also uses polymers that can be processed into powder form, including most **thermoplastics**. Most polymers are **ductile** and have low **electrical conductivity** and high **chemical resistance**. Low conductivity makes polymers useful **insulators**, while chemical resistance improves their ability to withstand corrosion. Polymer is often used for **rapid prototyping** but also can be used for **end-use** parts.

Powdered ceramics can also be used in L-PBF applications. Ceramics are hard and brittle. They provide parts with very high **heat resistance** and low electrical conductivity. Glass is the most common ceramic material used in L-PBF, but other materials, including carbon fiber, can also be used. Some ceramic parts processed with L-PBF include a **binder** material, such as **nylon**, to help fuse the ceramic particles together.



Metal Turbine Blade, courtesy of Xact Metal

A range of materials can be processed into powder form.

Laser powder bed fusion has a wide range of applications. It is most commonly used for building small- to medium-sized parts, though some machines are designed for larger builds. The wide range of materials available for L-PBF is also suited for various applications.

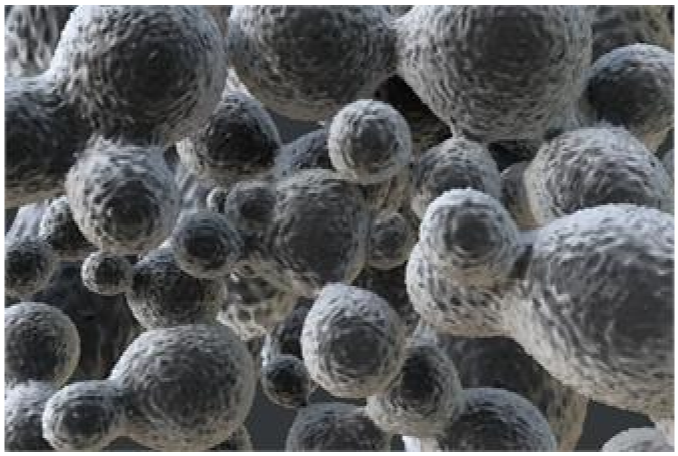
Like other metal AM methods, L-PBF is most often used for aerospace components. L-PBF can create parts with highly complex geometry and parts made of various metals and **alloys** that combine desired properties, such as **ductility** and **strength**, in a single assembly.

Many automotive part manufacturers have adopted powder bed fusion to produce unique parts such as car bumpers, exhaust **manifolds**, and other components. L-PBF enables more design options to improve functionality, faster design-to-production speeds, and greater flexibility for **mass customization** than traditional manufacturing methods.

The medical equipment industry uses L-PBF for a range of production purposes. L-PBF can use ceramics to develop dental implants, knee and hip replacements, and other bone structures. Some specialized L-PBF applications also use **biomaterials** for **tissue engineering**.

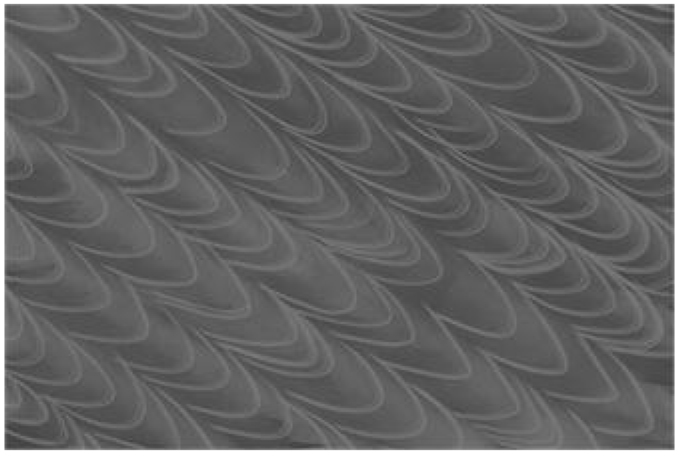
Manufacturers can use L-PBF to improve the geometrical design of components to add functionality. For example, adding **conformal cooling** channels improves heat management. L-PBF can also be used for lightweighting by creating **honeycomb structures** or **lattice structures** in the part's interior. This reduces the amount of material. When produced by traditional manufacturing processes, the same type of part would typically be completely solid.

L-PBF uses one of two types of machine that are designed for either selective laser sintering or selective laser melting.



SLS fuses layers, leaving some porosity.

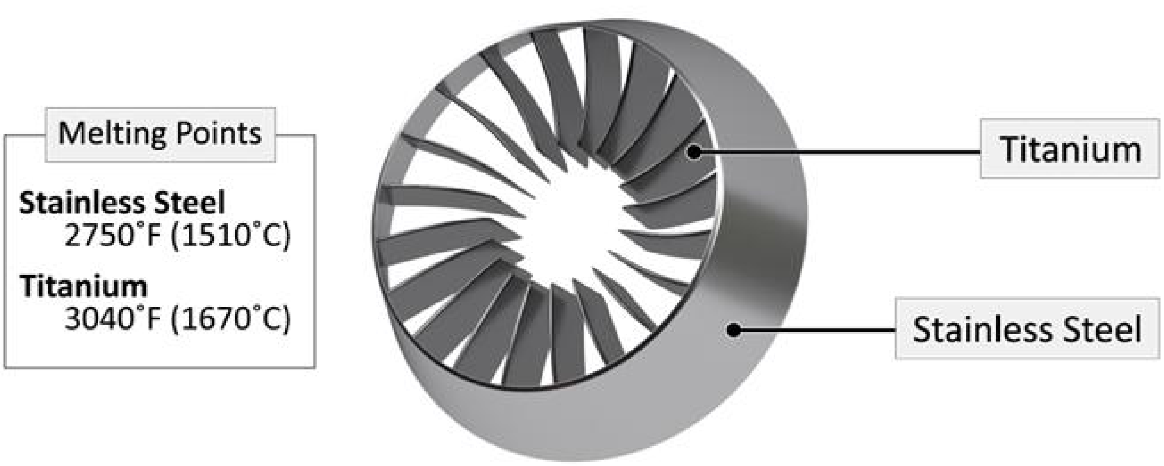
In **selective laser sintering** (SLS), the powdered material is heated to a temperature below its melting point that allows the powder particles to fuse together. The SLS process can sinter polymers, ceramics, or different types of metal alloys together by adjusting laser temperatures. When used with powdered metals, SLS is often referred to as **direct metal laser sintering** (DMLS). Because it uses lower temperatures, SLS produces little or no heat distortion and can create strong, highly accurate builds. However, SLS part builds typically have some **porosity** between fused layers.



SLM melts layers, eliminating porosity.

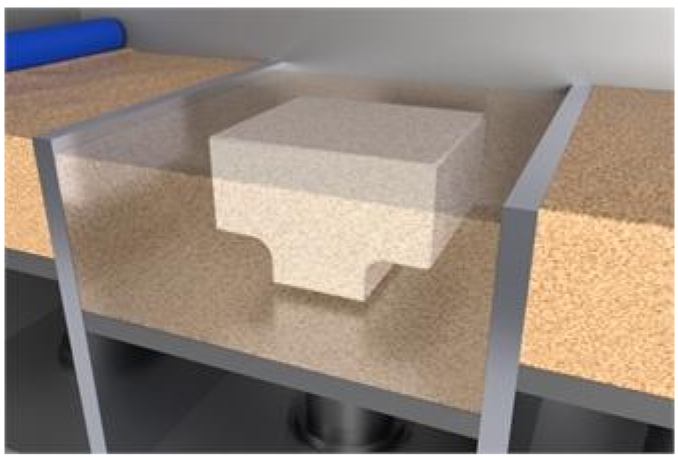
Selective laser melting (SLM) heats the powdered material above its melting point. Unlike SLS, SLM completely melts the material to create a single, solid-state part with no porosity between powder particles. SLM is most practical when using a single type of material since using alloys or multiple materials involves more than one melting point. Since it fully melts the material, it can produce high-performance parts that are stronger and denser than parts produced with SLS. However, fewer types of material can be used with SLM than SLS. It also uses more laser energy than SLS, which can cause more heat distortion.

L-PBF machine operating conditions, material considerations, and other factors will vary depending on whether a manufacturer uses SLS or SLM.



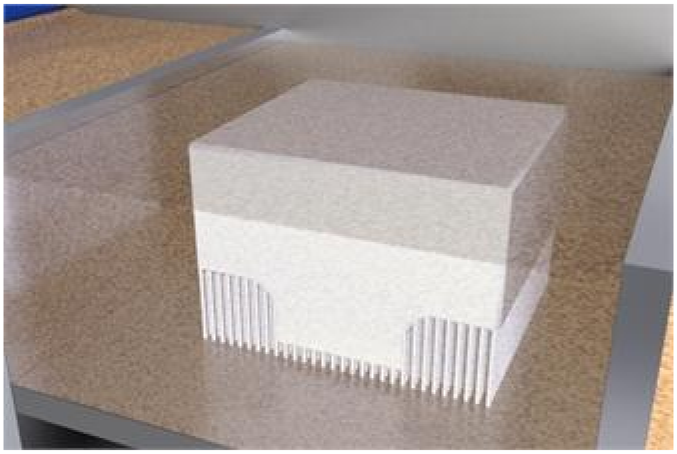
Melting points of different materials affect laser power settings for SLS and SLM.

In both SLS and SLM, each material requires different temperature settings and other parameters that design engineers and operators must consider. **Thermal stress** from the laser heat source is a primary consideration for L-PBF design and production processes. Designers and manufacturers must use appropriate heat settings for different materials to prevent defective parts. **SLS** processes' lower temperatures create less thermal stress than **SLM**. However, many of the alloys and **MMCs** used with SLS contain materials with different melting points. The laser must provide enough heat to fuse materials with higher melting points, which may cause some thermal stress for materials with lower melting points. When using SLM, designers and operators must account for more thermal stress and more potential inaccuracy than with SLS due to the higher operating temperatures. Since the SLM process completely melts the material, expansion and shrinkage typically occur as the metal melts, then cools back into solid form. While there is little or no distortion with SLS, some powder may not fuse properly during the SLS process, and parts may also have porosity, which is not a concern with SLM.



Passive Support

L-PBF processes, especially SLS, often use the loose powder in the bed itself to support free-standing parts and overhangs instead of using **support structures**. This is sometimes called the **passive support** method. Passive support provides advantages such as enabling complex build shapes, reducing material costs, and allowing multiple parts to be produced in one build cycle. However, using passive support instead of a build platform may result in more powder being heated but not completely fused. The material properties of this unfused powder may be altered, which can create problems with recycling the powder.

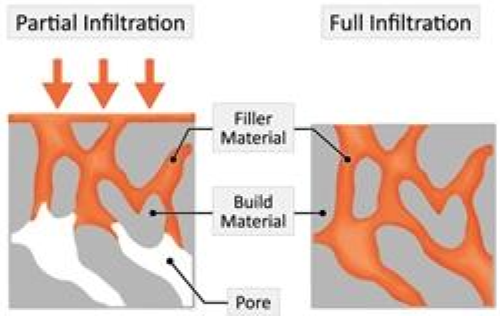


Active Support

Some L-PBF applications, particularly high-temperature SLM, use support structures in order to prevent part distortion that can occur during the build process. Building support structures onto the build platform to support overhangs and other features is often called the **active support** method. Support structures provide a base to allow better heat flow during the build process, which can reduce the amount of thermal stress on the material used in the build. Manufacturers must remove support structures using cutting tools and often use **computer numerical control** (CNC) machines for this. Part designers must consider how the build will be oriented on the CNC machine when designing parts that use support structures.

Like other AM processes, L-PBF usually requires **post-processing** operations once the part is complete. L-PBF processes, particularly SLS, produce parts with greater accuracy than **extrusion**-based systems. L-PBF can build parts to **net shape**. However, SLS parts require **finishing** processes to remove loose, unfused powder and correct poor surface finish. These finishing processes may require grinders, **end mills**, and other finishing tools. Since SLS produces parts with some porosity between particles of the build material, other processes, like **infiltration sintering**, may also be necessary. The infiltration process melts a filler metal into the finished build in order to fill in pores and increase the part's density.

SLM methods may require cutting tools to remove support structures once the build is completed. Additionally, the higher temperatures used in SLM create wider **temperature gradients**. Temperature gradient measures the rate of temperature change with distance in a given direction. Wider gradients on a part build mean more extreme temperature changes, which can result in greater distortion and shrinkage of the material particles. Distortion and shrinkage can cause permanent changes that make part dimensions less accurate. For this reason, parts produced by SLM may require **heat treatment** after or even partway through the build process to reduce thermal damage, and finishing tools to machine the completed part down to its original CAD dimensions in order to meet high **tolerances**.



Infiltration sintering increases part density.

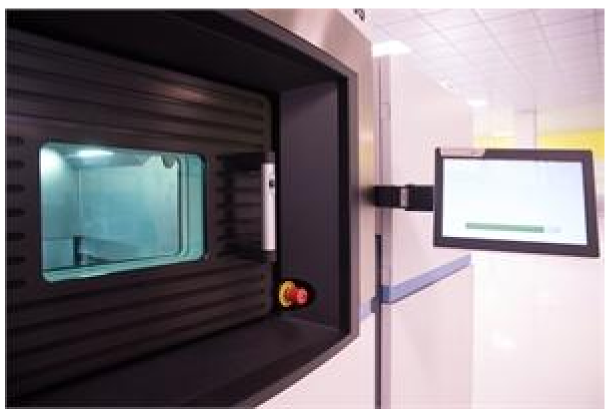
Abrasive Finishing

Compared to most other AM methods, L-PBF excels at creating highly accurate, complex builds. SLS in particular creates highly accurate dimensions due to little or no heat distortion . SLS's accuracy is similar to the accuracy of **binder jetting**, an AM method that fuses parts at room temperature, but SLS can also build stronger parts with greater durability than binder jetting. L-PBF is also one of few AM processes that can print metal parts for end use. **DMLS** specifically allows manufacturers to build parts made of various metals and alloys.

While L-PBF enhances design possibilities, it also has limitations that are important for designers to consider. Most L-PBF machines have a limited build size and cannot apply different materials to one build as easily as extrusion methods. This can result in slower build times for parts designed with multiple materials. With L-PBF, one powdered material must be removed from the powder bed before another material can be used in the process. L-PBF also requires a sealed, low-oxygen chamber in order to prevent **oxidation** and contamination, while metal extrusion may only require a shielding gas.

In addition, L-PBF has greater up-front costs than other AM methods like **directed energy deposition** (DED), which melts and deposits powdered metal through a small opening in a nozzle, because L-PBF requires more powder. However, since unused powder can be recycled, effective project planning can achieve savings over the long term.

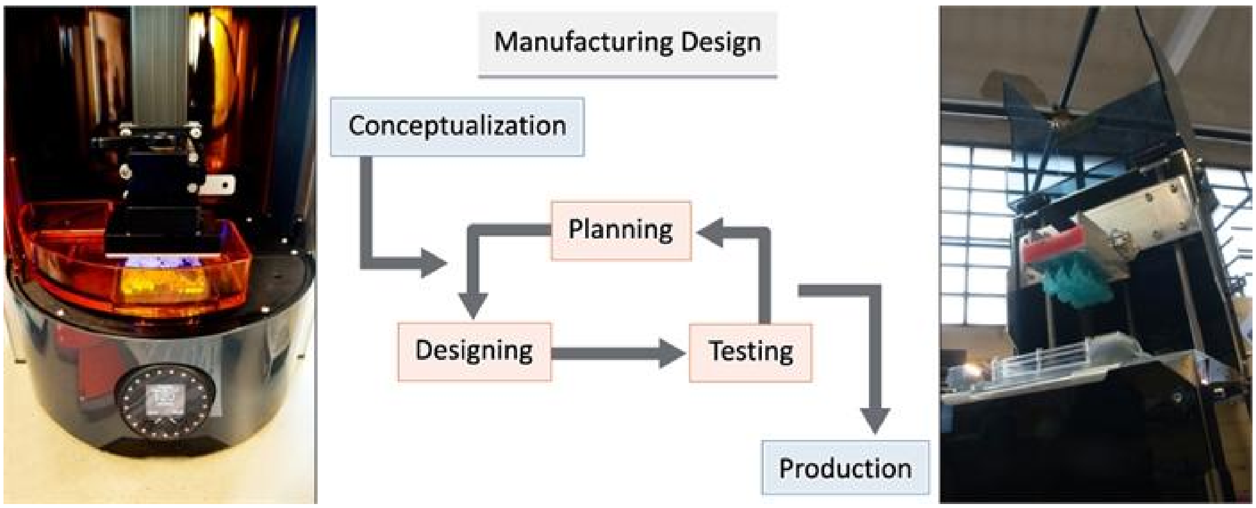
Complex Build



Build Chamber

305: Design for Vat Photopolymerization

Vat photopolymerization, such as **stereolithography** (SLA) or **digital light processing** (DLP) processes, is one technique in a larger group of building methods referred to as **additive manufacturing** (AM).



Vat photopolymerization machines use concentrated **ultraviolet** (UV) light to **cure**, or harden, liquid **photoreactive resins**, or **photopolymers**, layer-by-layer to form a solid part. Vat photopolymerization is the oldest AM technology. Because vat photopolymerization is used by **desktop** hobbyists utilizing consumer-level machines, it is commonly associated with the term **3D printing**, though the process is also used in large industrial-level machines for **end-use** part production.

Although each AM method requires specific equipment, they all follow the same basic five steps of the **design for additive manufacturing** (DFAM) process: **conceptualization**, **planning**, **design**, **testing**, and **production**. The flexibility of vat photopolymerization and other AM methods enables engineers to consider things like part functionality, optimized **topology**, and customization. The planning, designing, and testing steps also offer AM designers opportunities to increase production efficiency. Unlike more traditional types of manufacturing, altering an AM part's design does not require additional tooling or machine configurations.

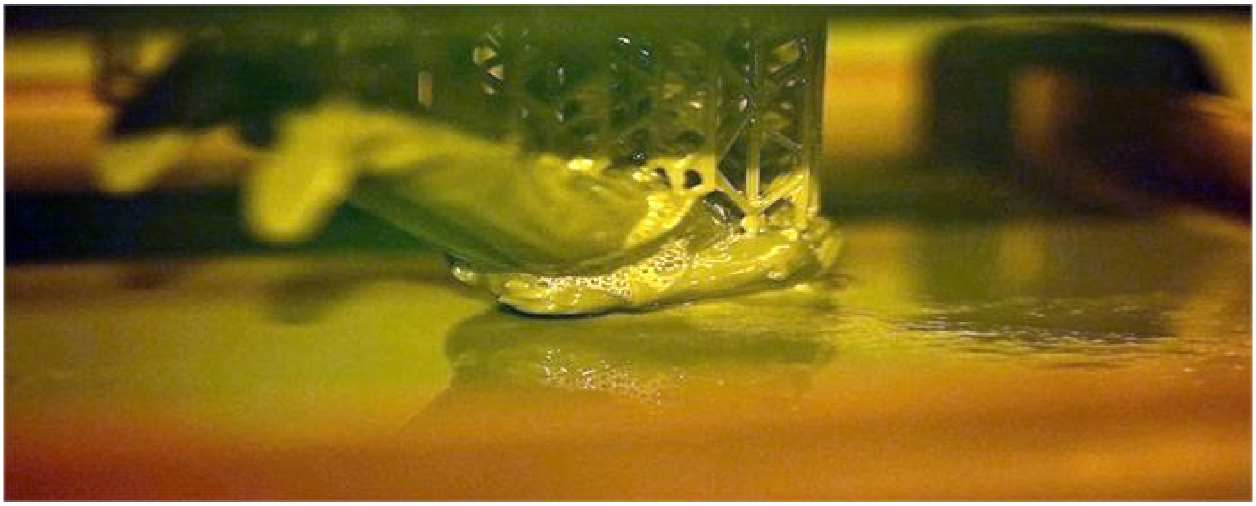
All vat photopolymerization systems consist of four general components: resin tank, or vat, with movable platform, liquified photoreactive resin, a light source, and a device that controls and directs the light. Light sources for vat photopolymerization include **lasers** and **light-emitting diodes** (LEDs). Liquid resins are typically made of photopolymers but can consist of other materials such as **ceramics**.

Vat photopolymerization systems can vary in how they build parts. Some systems may build objects from the bottom up, which requires an optical window in the bottom of the tank to allow light and small amounts of oxygen into the vat. The small amount of oxygen creates a thin air pocket, or deadzone, right above the optical window. The oxygen deadzone prevents the liquid resin from curing in that space, which keeps the part from sticking to the vat floor. During the build process the platform moves incrementally upward, drawing the part out of the vat as it completes each layer. Other machines may build objects from the top down, which requires a light source above the vat curing each layer as a build platform incrementally lowers. Once a layer is completed, a **recoater** uses a blade to smooth a new coat of liquid resin over the previous layer. Differences in component and arrangement can affect the quality, cost, and speed of the vat photopolymerization process.

Vat photopolymerization includes several different processes, some of which are **proprietary**. The two most common vat photopolymerization processes are **SLA** and **DLP**, which differ in the way they each project light onto the surface of the photopolymer build material.

SLA, one of the original AM processes used in manufacturing, projects light from a single-point source onto the surface of the liquid photopolymer. When the light hits the liquid resin, it hardens. The light moves in a precise pattern, tracing out the part's shape and eventually creating a solid part layer.

DLP uses a specialized projector that displays a part layer as an entire image on the liquid photopolymer resin. Instead of a single-point source, DLP projectors generally have a thousand tiny light sources focused on the build platform. Upon contact with the projected light, the resin cures and forms a solid part layer all at once.



Part being lowered into liquid resin.

Vat photopolymerization often uses a specialized liquid form of **thermoset** plastic photopolymer resin, which permanently hardens when exposed to **UV** light. The fluid nature of this type of photopolymer enables the build platform to move easily inside the vat for SLA systems as the machine builds the part layer-by-layer. Though they are always liquid, materials used in vat photopolymerization systems can vary beyond plastics. For example, some systems can use photopolymer-based composites, which are infused with ceramic powders. Composites allow manufacturers to build parts with specific or enhanced properties, such as increased hardness.

Most resin types used for vat photopolymerization are proprietary, or made specifically proprietary, or designed by a specific company for use only with its own systems. Sometimes resins are designed to imitate popular plastics, such as **acrylonitrile-butadiene-styrene** (ABS) or **polypropylene** (PP). In other instances, manufacturers may develop resins to replicate the qualities of wax for more effective **castings**. Although manufacturers can recycle unused liquid resin, once a UV light cures a photopolymer, it is permanently altered and cannot be melted again.

Typically, the liquid resins used with vat photopolymerization fall into general categories based on their properties. For example, industrial vat photopolymerization machines generally use resins with a wider range of properties than desktop machines. For both types of machines, common resin categories include: standard, transparent, tough and durable, castable, and biocompatible.

When selecting a build material for vat photopolymerization, an engineer or designer must consider several factors, including the size and type of vat photopolymerization system. Desktop printers work well with **standard resins** that emphasize appearance, which makes them ideal for low-cost prototyping. Standard resins produce parts that have smooth, even surfaces and are generally **brittle** and have higher **stiffness** than other materials. However, standard resins are usually quicker and cheaper to print than other resin types, which makes them ideal for **iterating** part concepts or **rapid prototyping**.

Transparent resins produce parts that are **translucent** or clear. Manufacturers use transparent resins to build products and prototypes for camera lenses, lighting, and consumer electronics.

Large industrial vat photopolymerization machines use a wider range of materials than desktop versions. Typically, industrial machines are designed for end-use production, so **tough resins** that have functional properties such as **strength** and **heat resistance** are optimal. Tough resins for vat photopolymerization have a durability that typically mimics the properties of popular plastics used in engineering. These plastic types can include **ABS** and **PP**. Common applications include automotive components, electrical housings, pipe fittings, and objects with **single-snap features**.

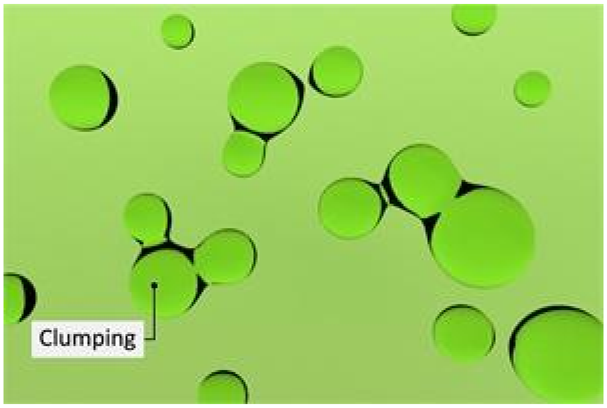
Designers may use **castable resins** as a cheaper alternative to traditional casting and moldings. For example, an engineer may use vat photopolymerization to create **master patterns** for **investment casting**, which can create intricate shapes using a a single-use pattern or mold, which cannot be reused again. In contrast, engineers may also use heat-resistant resins to build a reusable master pattern, which can make multiple molds. Common applications can include aerospace components, molds and cores, or even jewelry.

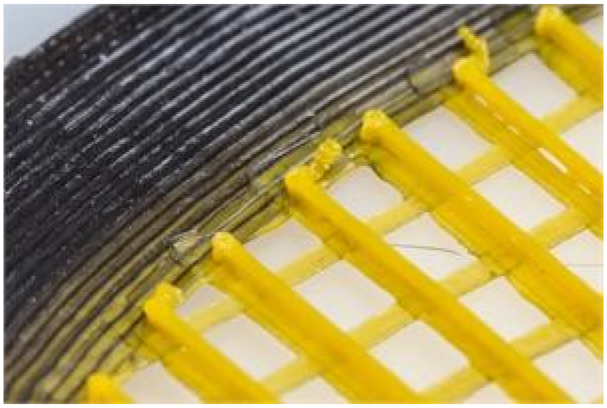
Biocompatible resins, which are compatible with living tissue, allow medical and dental professionals to use vat photopolymerization to create parts with intricate features. Vat photopolymerization's ability to produce a high level of detail makes it suitable for building customizable medical implants, dental **prosthetics**, and hearing aids.

Manufacturers must carefully consider **environmental factors** for storing and using materials. Materials used with desktop printers generally have fewer environmental factors compared to materials designed for industrial use.

Exposure to light can degrade photopolymer resins, which can impact **repeatability**, or the ability to produce consistent and uniform results. Temperature fluctuations can also affect the quality of a resin, causing it to clump in some situations. Best practices for resin storage include a steady temperature and no exposure to light.

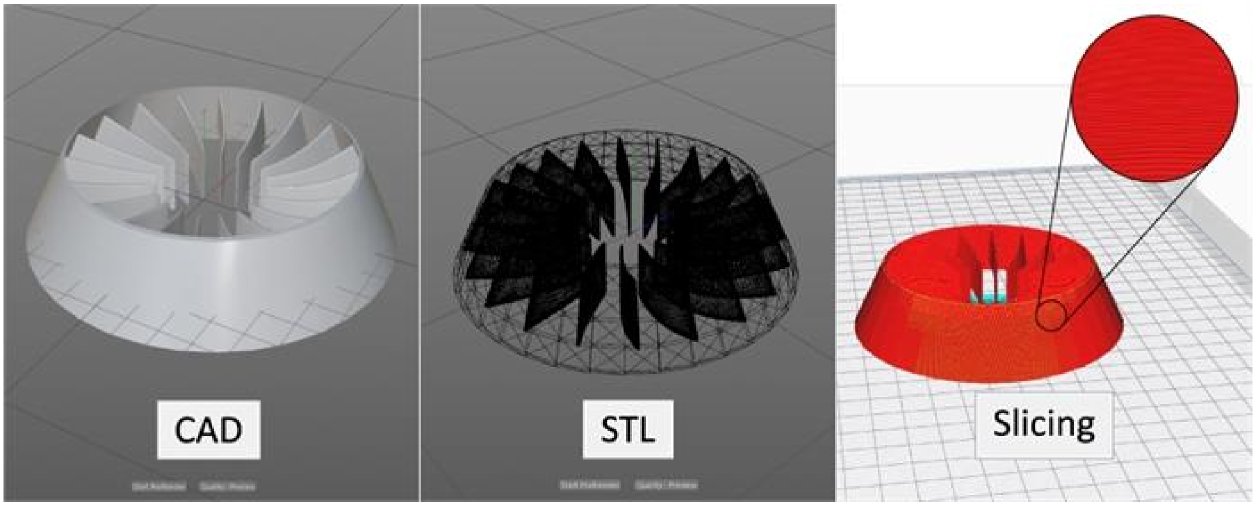
Resins used with SLA and DLP machines are similar, but not always compatible across machines. For example, a traditional single-laser SLA printer slowly traces the build area, so a resin that cures slower may be necessary to create accurate part layers. In contrast, a DLP machine prints an entire layer at a time, which requires a faster-curing resin. When light penetrates a resin too deeply, it may cure unintended areas and affect the dimensions and details of a part. When too little light or heat causes a resin to under-cure, it may affect **layer adhesion**. Designers should consult the resin data sheet to ensure compatibility with vat photopolymerization systems and processes.





Layer Adhesion

Like other AM methods, vat polymerization design processes use **software**, often **computer-aided design** (CAD) software, to create a three-dimensional (3D) design file of a part. A CAD file is a digital representation of a physical part.



However, AM machines cannot directly read design files. Because of this, a designer must convert the 3D design file into an **STL** file format. STL software converts the geometry of a 3D model into a sequence of interconnected triangles that represent the surfaces of the physical part. Next, digital **slicer** software "slices" the STL file, or translates it into digital versions of the layers that the machine will cure to physically build the part.

The digital slicer software then converts the layer information into **G code**, a numerical programing language that controls the functions and motions of machine tools like vat photopolymerization machines. Essentially, digital slicer software breaks a digital model into the layers of material that the vat photopolymerization machine will cure, while the G code program directs the light projection components and platform movements.

Some common part structures may cause issues during vat photopolymerization part builds.

Designers should take special care with the first layer of a vat polymerization part. Typically, an operator must **calibrate** a vat photopolymerization machine to balance the **exposure time** and light **resolution** with the part's layer width. Incorrectly calibrating may lead to under-curing, which can cause a layer to detach from the build platform or even fall off. To avoid this, some designers will expose the first layer to UV light longer to ensure adhesion.

If the first layer of a part has a small build area, it may create design issues. When using a bottom-up system, the weight of the part may cause it to break away from the build platform during the part build. To avoid this, designers may incorporate a wider first layer to better anchor the part on the build platform.

Layer warping, or **curling**, presents another design issue for vat photopolymerization. The energy from the UV light source causes each part layer to shrink slightly. If too much shrinkage occurs, it may cause internal stresses within the part.

Designing a part with proper internal and external **support structures** may help alleviate part stress and ensure the entire part holds its shape during the curing process.

If a part design has branched structures, the intersection points where two branches meet may crack or even break. Using a rigid resin type may help alleviate problems associated with intersection breakage. Optimizing the position of a part during printing, or **part orientation**, may also help prevent this issue. For example, by positioning the branches outward allows the intersection point to act as an anchor for the part.

It is also important to adequately support the base or lowest component of a part. Under-supporting the lowest point in a part structure can lead to breakage and warping during the vat photopolymerization process. To present potential defects, a designer may need to add a stronger **anchor point** where support structures and the main area of the part meet.

> Every part designed for vat photopolymerization requires external support structures, which reinforce part components during the build process.

How a designer uses external structures depends on the vat photopolymerization system. For example, in a top-down system, a part will need external support structures for any **bridges** or **overhangs** that extend beyond a 30° angle. However, a top-down system can print flat parts with limited external support.

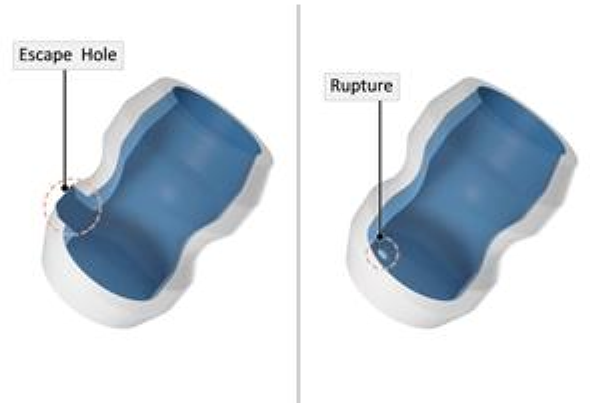
In contrast, printing a flat part in a bottom-up system can lead to part stresses. A designer may therefore use support structures to angle a part, which reduces stress on its cross-sectional area during printing. This significantly reduces the risk of breakage and curling.

Designers may also use support structures to put a part on an incline, which can significantly increase the quality of the printing. In addition, placing the longer support structures nearest to the recoater blade can increase the print speed, since the blade has less distance to travel on the machine.

In some cases, designers may interconnect support structures to provide sturdier support for heavier parts. However, in general the additional resin used to create support structures increases the overall cost of the part.

To avoid extensive **post-processing**, vat photopolymerization designers orientate the part so that external support structures are used in the least visible part areas, which prevents support blemishes in the most visible areas of a part.

In addition to external structures, vat photopolymerization processes utilize internal support structures.



Adding escape holes can reduce cupping.

In order to reduce material costs and decrease print time, vat photopolymerization designers may make the internal structures of non-functioning prototypes and parts hollow. However, liquid resin trapped in these hollow areas may cause the part to become unstable during the printing process. Bottom-up systems in particular may experience a type of part rupture referred to as **cupping**. In cupping, liquid photopolymer becomes trapped within a hollow part, which creates a suction-like force that can rupture part walls during the build process. Adding escape holes to the part design, which allow the liquid to flow out of the part, can reduce the risk of cupping.

Internal support structures can reduce stress fractures.

Designers may use a variety of internal support structures to reinforce the thin walls of a hollow part or help join pieces together. For example, a raised, circular protrusion with a hole in the center, called a **boss**, may guide a screw or pin of a **mating part** to help improve part assembly. Designers may also add a support **rib** to increase the stiffness of a part and help reduce potential warping. Using rounded part corners instead of sharp corners may also help reduce the potential for **stress fractures**.

Removing support structures by hand.

After printing, most vat photopolymerization parts will need post-processing or **finishing** procedures to clean, improve, or create an attractive surface finish on a part. External support material must be removed, which requires specific techniques to avoid damaging any delicate part features. Once parts are printed, an operator typically removes support structures by hand. Often, completed vat photopolymerization parts are cured again to further solidify and strengthen the part.

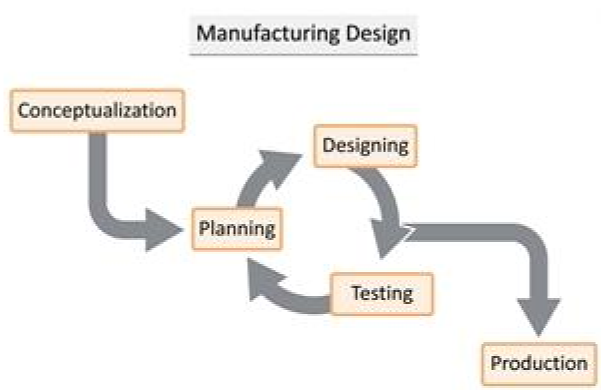
Post-processing can improve surface finish and remove blemishes or imperfections that may have occurred during the vat photopolymerization process. Because post-processing may add material to or remove material from a part, designers must factor it into their part designs. For example, sanding and other abrasive finishing processes remove small amounts of material from the part's surface. If a part needs to be filed or sanded, a vat polymerization designer should build the part a little larger to account for the removed material. Painting or adding other coatings increases a part's size slightly, so in these instances, the designer should design the part slightly smaller to account for the additional material. Other parts may present multiple finishing or post-processing options to achieve different affects. For example, operators might apply a clear coating to a transparent surface to give it a more vibrant finish. In some instances, adding a **mineral oil** coating can also help give a part an even finish.

306: Design for Binder Jetting

Binder jetting is one technique in a larger group of building methods referred to as **additive manufacturing** (AM), which is sometimes referred to as **3D printing**. Binder jetting machines use a print head to dispense a liquid **binding agent**, like a glue, to selectively join raw material powder layer-by-layer in a **powder bed** in order to form a solid object. Binder jetting can build parts from powdered metals, ceramics, or sand.

Although each AM method requires specific equipment to build parts, they all share the same basic five steps of the **design for additive manufacturing** (DFAM) process: **conceptualization**, **planning**, **design**, **testing**, and **production**. The capabilities of binder jetting enable engineers or other designers to conceptualize things like part functionality, complexity, and customization. The planning, designing, and testing steps offer AM designers opportunities to increase production efficiency, since binder jetting machines can have a larger build space compared to other AM processes. Binder jetting is commonly used to produce a large number of parts at a low cost.

Binder jetting print heads dispensing liquid binding agents. Courtesy of The ExOne Company.



The binder jetting process has two basic stages. The first stage begins with loading the raw material into the machine's **hopper**. The machine transfers the material **powder** from the bin into a **recoater**. The recoater is a hollow device that carefully spreads the powder in very thin layers on top of the **build platform**, which is the movable flat surface located in the machine's **powder bed**. The powder bed, or build box, holds the granulated build material and the build platform.

In the second stage, an inkjet-type printhead deposits small amounts of a binder agent to selective areas of the powder on the build platform. The binder agent connects particles of the powder together to form a solid layer. Once a layer is complete, the build platform lowers in the powder bed to accommodate the next part layer, and the two stages repeat themselves. With each layer, the part forms only in the selected areas where the print head deposits the binder. The unused powder remains in the job box while the machine builds the part and can be recycled afterwards. Once built, an operator extracts the part in its **green** state, which is typically fragile and may need **post-processing** before complete.

Binder jetting can work as a successful method for a variety of manufacturing applications. Many companies currently use binder jetting for making prototypes or building complex parts in small batches. However, a growing number of industries have adopted binder jetting as a viable option for the **mass production** of end-use components.

Binder jetting can offer high design flexibility at a lower cost than traditional manufacturing methods. For example, many manufacturers use molds to create castings in a **foundry**, where the mold is filled with molten metal such as **cast iron** to create a part. Binder jetting can create molds with complex internal structures in one piece, while traditional manufacturing molds may create complex structures in multiple pieces and then bond them together. Manufacturers in the aerospace industry, for instance, have integrated binder jetting technology into their production strategy in many ways. Aerospace companies commonly use **sand** with a binding agent to create a **casting** or **core** for complex engine components such as a **water jacket** or lightweight structural **hinges**.

Binder jetting can also be used for **lightweighting**, or designing parts that weigh less but function the same as traditional parts. In the automotive industry, the binder jetting process can help automakers produce lighter parts to increase fuel efficiency and speed. For example, manufacturers can produce brake **rotors** made of **silicon carbide**, a ceramic material that is lighter than traditional metal.

Binder jetting also has many versatile applications for the medical field. For example, manufacturers can use binder jetting methods to create thin metal air filters for **respirators** and other medical equipment. Unlike regular **personal protection equipment** (PPE), which is typically disposable, these air filters made of metal may be sterilized and reused. This reduces waste and costs.

Engineers can also use binder jetting to design more effectively with **concrete**. For example, construction engineers can use binder jetting to create complex casting molds for concrete smart slabs that maximize stability while using much less material. The smart slabs can also include functional spaces for things like electrical wiring, light fixtures, and fire sprinklers. Engineers may also use binder jetting processes to fabricate concrete itself using cement powder and a binding agent. Binder jetting concrete allows engineers to design elements of a building with unique geometries and detailed designs that are beyond the limitations of most traditional manufacturing processes.

There are many unique factors that an engineer must consider when designing and creating a part with binder jetting.

Binder jetting has some advantages when compared to **fused deposition modeling** (FDM) and other **AM** processes. The binder jetting process works at room temperature, so it avoids **thermal distortion** and other issues experienced by AM processes that use heat to build parts. In addition, the loose powder in the powder bed supports the part during the build. FDM and other AM processes also require **support structures** to hold any overhanging part features during the part build. These must be removed once the part is complete, which uses extra time and materials. Since the powder bed provides support, the binder jetting process requires no support structures. This saves time, reduces material cost, and streamlines post-processing.

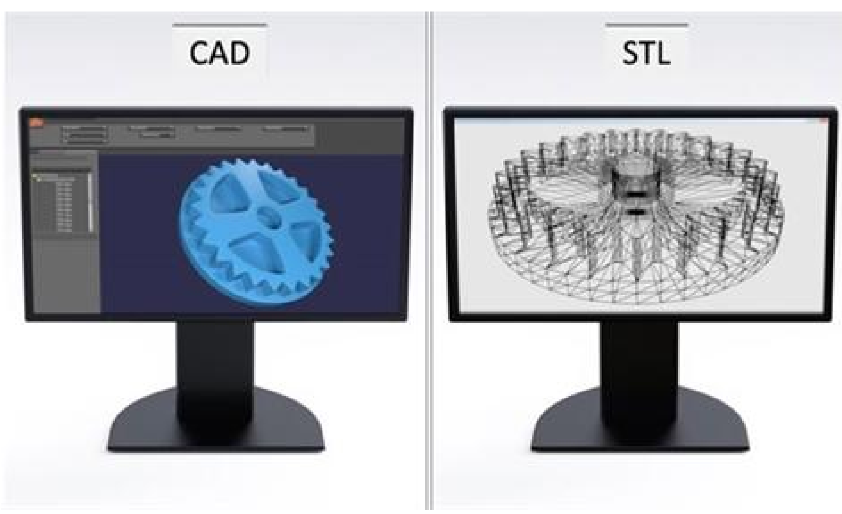
Binder jetting machines generally have the largest build area of any of the AM processes. This makes binder jetting appropriate for printing large parts, such as an **engine block**. Binder jetting can also utilize multiple printheads to build large machines at a faster pace compared to other AM processes. When producing large parts, however, designers should consider size restrictions of secondary processes like **sintering**.

Larger build spaces can also increase the amount of smaller parts that a binder jetting machine can build at one time. Because binder jetting requires no support structures, this gives designers more freedom to utilize the entire dimensions of the build box. For example, designers can increase the quantity of parts made in a single build by stacking parts on top of each other in the build box.

Designers can also use binder jetting to **lightweight** a part, which is a design technique that replaces one part or object with a lighter version for identical use. For example, a designer can take a structural part made for an automobile and use binder jetting to create a complex design for the same part that is nearly half the weight with less material waste. In addition, binder jetting may enable a designer to increase production speed by reducing the production steps in the manufacturing process. It can also simplify the way a part is integrated into the assembly of the vehicle by designing a smaller weld area.

Compared to other AM processes, binder jetting typically has higher rate of **repeatability**, which refers to the ability of a manufacturing process to produce consistent and uniform results. Because of this, designers can use binder jetting processes for the serial production of parts. The serial production of parts enables designers to produce batches of exactly the same part.

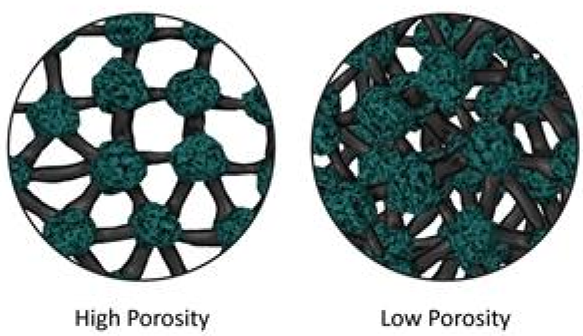
Like other AM methods, engineers or other designers for binder jetting use **software**, often **computer-assisted design** (CAD), to create a 3D design file of a part. The CAD design file is a digital representation of the physical part, but binder jetting machines cannot directly read design files.



Because of this, an engineer must convert the 3D design file into an **STL** file format. The function of the STL is to convert the geometry of the 3D model into a sequence of interconnected triangles representing the external surface of the design. Digital **slicer** software takes the STL information and translates it into 2D layers that the machine uses to physically build the part. Next, the digital slicer software takes the 2D layer information and coverts it into **G Code**, a numerical programing language that controls the binder jetting machine's functions and motions. The digital slicer software constructs the layers of material that the binder jetting machine will deposit and bind as it uses the printer head to build the part. The G code program then directs the print head back and forth across the build platform. As the print head moves, it deposits binder in precise locations, similar to an inkjet printer depositing ink in specific patterns on paper.

An engineer or designer must consider several material factors when designing for binder jetting. Binder jetting systems typically build parts from a limited range of material types: sand, ceramics, and metals. Once a binder jetting part is printed, it is considered in its **green** state, which is generally weak. The weakness of green parts comes in part from its high **porosity**, which refers to the empty spaces between the grains and bond in a binder jetted part. Compared to other AM processes, binder jetting parts typically have lower **mechanical properties**, like **strength** and **ductility**, and are more likely to fracture when subjected to force. Because of this, binder jetting is generally better suited for building low-performance parts. However, manufacturers can build complex parts with binder jetting at a much lower cost than other methods.

A part's end use determines the ideal part material. For example, if a customer needs a casting mold for an engine part with a complex geometry, sand is likely the ideal build material. If a customer wants to improve the efficiency of an existing metal part, like a **filter**, a designer can utilize the dimensional accuracy of the binder jetting process to create a more efficient design that is more economical to produce, without the added costs from support structures or scrap.



Filters. Courtesy of The ExOne Company.

Binder jetting can use a variety of **raw materials** in powder form to build a part. Commonly used raw materials for end-use production generally fall into three categories: sand, ceramic, and metal. When selecting the best material for a project, designers must consider factors such as uniformity, tolerance, and post-processing characteristics.

Sand is most used with binder jetting machines to print molds and cores for sand casting processes because it works better with metal. Binder jetting can use both **green sand**, which occurs naturally from crumbling rocks, and **synthetic sand**, whose properties and mixture content is artificially controlled. Green sand is generally cheaper to use compared to synthetic sand. However, the size and shape of green sand granules form in irregular patterns making it more unpredictable to use. In contrast, synthetic sand is formulated to have uniform properties, which makes it better for mass production.

Powder metals used with binder jetting are typically **alloys**, a type of metal consisting of a mix of two or more elements. **Stainless steel** is a common alloy used with binder jetting because of its excellent corrosion resistance and hardness. Other examples of alloys used with binder jetting include **Inconel**, which performs well in extreme environments, such as aerospace components.

Although less common than sand and metal, binder jetting systems may also use ceramics, a material consisting of compounds formed by metallic and nonmetallic elements. Common **ceramics** used with binder jetting include silicon carbide, known for its resistance to high temperatures and electricity, and **aluminum oxide**, favored for its toughness and long life.

Binding agents are an important part of the binder jetting process. Liquid binders come in a variety of materials and are combined in a variety of different ways. When printing a part, designers should choose binding agents that both work advantageously with the raw material and correspond to its end-use function.

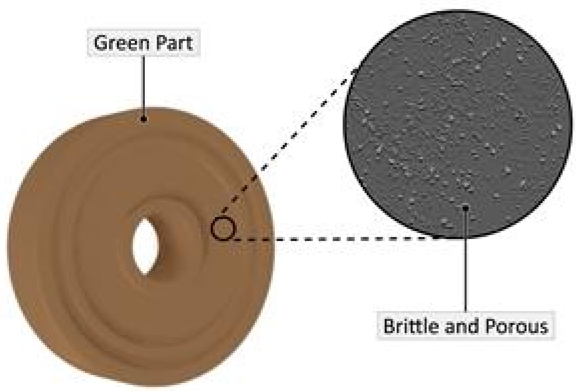
For example, some sand molds can be used in castings while in their green state, so a designer may choose a **furan** binder that enhances green part strength. Furan is a general term for binders that contain **furfuryl alcohol**, which is commonly used in traditional foundries. Sand molds made with furan binding agents are ready for casting soon after printing and do not require any thermal post-processing treatment.

Other designers might use a **phenolic** binder to make sand molds, because it works better with higher temperatures and is **flame retardant**. Phenolics are a group of inexpensive thermoset polymers, which means they are permanently hardened by heating. Some phenolic binders can self-harden. However, many phenolic binders generally need some thermal processing like **curing**, which uses heat, **ultraviolet radiation** (UV radiation), or pressure to harden the **thermoset** material.

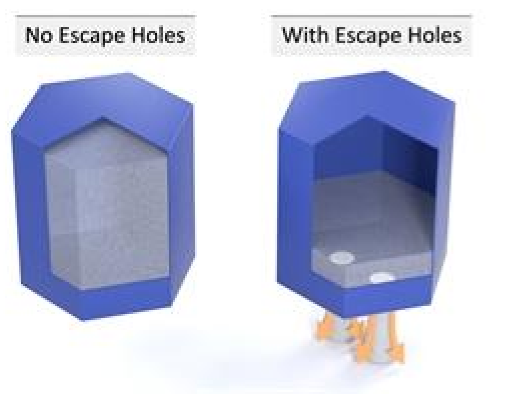
Like thermoset phenolics, a **polymer** binder is comprised of one or more types of plastic materials. Polymer is also a general term for binding agents used with metal powder. Polymer binders enable designers to create complex geometries with metal, but the fragility of a green metal part typically needs a secondary process known as **sintering**, which hardens and condenses a part through extreme heat. During the sintering process, polymer binders will melt or burn away, leaving only the solidified metal part. Because of this, polymer binders are also selected for their ability to burn off cleanly, which enables part uniformity across production and avoids performance problems created by carbon residue.

A manufacturer may use some types of sand molds and cores in their green state almost immediately after the binder jetting process. However, most binder jetting parts in their green state are brittle and porous, like a dried sponge. In order to strengthen the part, it may need **thermal** treatments or **infiltration** of another material. These processes may take several days to complete, so designers must plan these processes into their overall production time.

Designers must also design green parts with enough strength to withstand post-processing techniques. For example, a fragile part may break during the **de-powdering** process, which is an operation used to clean the parts.To compensate, a designer might add an **escape hole** to remove unbound material properly from a hollow area. They might also add a structural **brace** to strengthen the design. For example, a thin area of a part attached to a thicker area is more at risk to break during post-processing. Designing a brace for a potentially weak area would greatly reduce the risk associated with post-processing binder jetting parts in their green state.



Before infiltration.



Adding escape holes.

Post-processing methods for green binder jetted parts may include infiltration and thermal treatments, such as **curing** and **sintering**.

Curing can keep a part from breaking when being de-powdered. The curing process can happen at two different points during the binder jetting process. As an inkjet builds the part, a machine may lightly cure, or heat, each layer to help solidify the binding. Once the green part is completed, an operator loads the entire build box into the curing oven, which exposes parts to extreme heat for several hours. This additional curing both solidifies the material and melts away the binding agent. After curing, an operator can remove the part from the build box for de-powdering, infiltration, and other post-processing applications.

Burning away the binder agent gives the part high porosity, or many tiny empty spaces within the material. If the part must have high **strength**, designers may find it necessary to **infiltrate** a part after curing. Infiltration is the process of reinforcing a porous material by filling the tiny empty spaces with a melted or liquified material. Designers can use infiltration to add or enhance other material properties in addition to strength. For example, infiltrating a **stainless steel** filter with bronze increases its corrosion resistance and strength, making it easier to polish.

Instead of infiltration, it may be necessary to sinter a binder jetted metal part, which exposes it to extreme heat for two or three days. This intense heat compacts the part and reduces the porosity of the metal. If a part will be sintered after binder jetting, it is important to factor the expected amount of shrinkage into the initial part design. However, sintering may cause the part to shrink in unpredictable ways. To offset potential irregular shrinkage, operators can place **stilts** in some larger holes in a part. Stilts are small posts used to support holes or other open part features while they are exposed to extreme heat.

After infiltration or thermal treatments, a binder jetted part may still need additional **post-processing** or **finishing**, which is a group of procedures used to clean, improve, or finish a part. Post-processing can improve surface finish and remove blemishes or imperfections that may have occurred during the binder jetting process. Because post-processing may add or remove material to a part, engineers must factor it into their part design.

Applying a coat of paint.

Abrasive finishing is a group of post-processing methods that use grains of ceramics or other very hard materials to remove small amounts of material from a part's surface. Abrasive finishing processes use different methods and materials to smooth and refine part surfaces. Selecting the best method may depend on the part material. For example, common post-processing for metal binder jetted parts includes **polishing**, which may use a fine **grit** to smooth out surface marks and imperfections. Sand parts may require **abrasive blasting**, which sprays the surface of the part with dry particles of abrasive material, like glass, to smooth the surface without damaging the part.

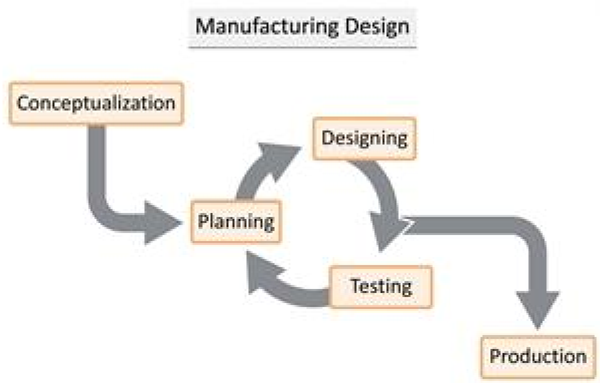
Other post-processing methods add material to part surfaces. For example, a common post-processing technique is to apply a coat of paint to uniformly smooth and color the surface of a part. Similarly, **plating** adds a thin layer of metal to a surface. Both painting and plating can enhance the appearance of the finished part. Additionally, adding coatings to a binder jetted part can protect it from exposure to harmful **chemicals** or other environmental factors.

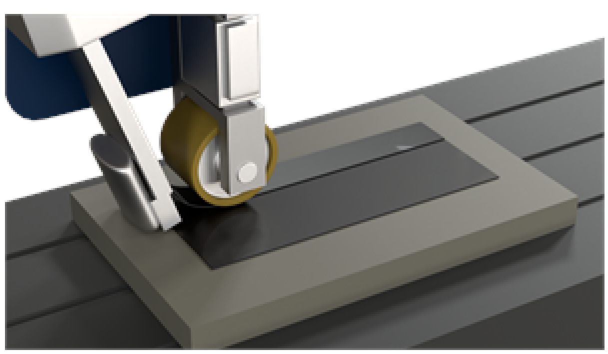
307: Design for Sheet Lamination

Creating parts with any **additive manufacturing** (AM) process involves following the same five basic steps. The first step of **design for additive manufacturing** (DFAM) is **conceptualization**, during which manufacturers determine the type of part and its functionality. The second step is **planning**, when they decide how to manage the workflow to produce the part. Next is **designing**, which involves generating a digital model and creating a **prototype** of the part. The next phase, **testing**, involves determining how the part functions and if it performs according to **specifications**. If the part passes testing, it is ready for the **production** phase.

The specific capabilities and limitations of different AM processes affect how engineers and manufacturers approach each phase of DFAM. **Sheet lamination** is an AM process that bonds successive layers of material to form a part based on a **computer-aided design** (CAD) model. The material **feedstock** used for sheet lamination comes in a **feedstock roll** installed on the sheet lamination machine. The feedstock roll is fed onto the machine's **build platform** in separate sheets which are bonded together. Sheet lamination can use a variety of different materials and bonding methods to create parts. The materials are cut into the shape of the part with **subtractive manufacturing** methods. Sheet lamination is often considered a **hybrid manufacturing** process because it uses both additive and subtractive methods.

This material is based upon research supported by, or in part by, the U.S. Office of Naval Research under award number N00014-18-1-2881 led by the National Center for Defense Manufacturing and Machining (NCDMM).





Sheet lamination processes are roughly categorized by the type of material they use.

The first sheet lamination machines used only paper materials to build parts. Sheet lamination processes that build parts from paper materials are currently used for **rapid prototyping** but not for producing **end-use** parts.

Some sheet lamination processes can use **polymer** materials. Polymers are plastic materials that include both **thermoplastics** and **thermosets**. Polymer materials can be used for rapid prototyping, but they are also useful for end-use products, like storage containers and medical equipment. Polymers are generally **ductile** materials with high **corrosion**- and wear-resistance. Polymer sheet lamination can use most common polymers, including **polystyrene**, **polypropylene**, **nylon**, and other thermoplastics.

Ceramic materials, including some **composite** materials, have become increasingly popular as sheet lamination technology has advanced. Common ceramics used in sheet lamination include glass, **cement**, and **ceramic matrix composites** (CMCs). Ceramic materials have very high heat- and corrosion-resistance properties and are suitable for a wide variety of end-use products. Composite materials, such as **carbon fiber**, can also have high heat- and corrosion-resistance, as well as high strength or other properties depending on the combination of materials.

Metal materials are the most common sheet lamination materials for building end-use products. Sheet lamination processes can produce parts from a wide range of metals, including **titanium**, **steel**, and **aluminum**. **Metal alloys** and **metal matrix composites** (MMCs) can also be used in sheet lamination.

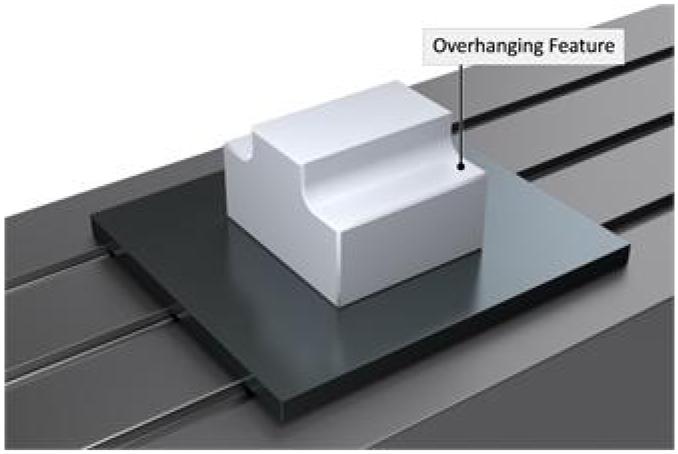
Like most **AM** processes, sheet lamination is commonly used to build parts for **aerospace** components. Sheet lamination processes can print a wide range of aerospace parts used for **drones**, aircraft, or space exploration, including engine components, wings, and other exterior parts. They are also used to build **housings**, **molds**, and other general components for aerospace assembly.

Sheet lamination processes are often used to create ceramic parts for medical applications. Ceramic medical components include bone structures, dental implants, and **microfluidic devices**. Microfluidic devices can transfer and digitally monitor small amounts of fluid in the human body. These devices are often used to diagnose illnesses but can also be used in artificial organs.

Sheet lamination can create parts made of different materials or different colors of the same material. In addition, sheet lamination can use a greater number of different materials in a single part more efficiently than most other AM processes. This is because a sheet lamination machine feeds material for a part one sheet at a time, and one roll of material can quickly be removed and replaced with another roll of material.

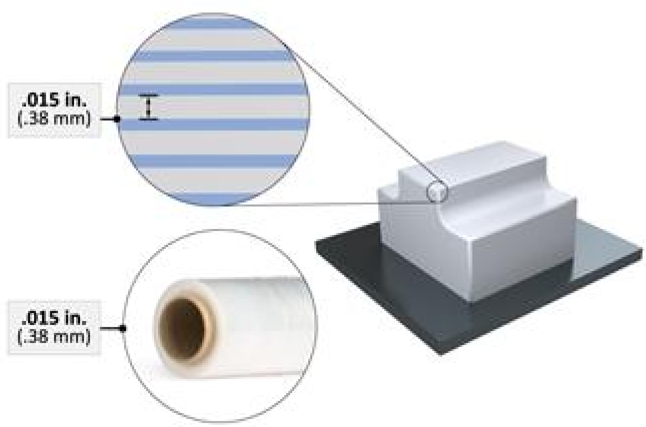
Because it is a hybrid manufacturing process, sheet lamination is often used to create complex internal features, like internal channels for enhanced fluid flow or **conformal cooling**. In hybrid AM processes, subtractive manufacturing tools can machine areas of a part throughout the build process as the part is constructed. This allows manufacturers to finish internal surfaces or create features in areas that would be inaccessible using traditional manufacturing methods. As a result, sheet lamination and other hybrid processes can create more complex parts in a single build process.

Sheet lamination has specific capabilities and limitations that part designers and manufacturers must consider.



Sheet lamination does not require support structures.

Sheet lamination uses cheaper materials than other AM processes and often prints parts faster, reducing both cost and production time. Since it builds parts by stacking sheets of material, sheet lamination does not require **support structures** to build **overhanging features** on a part. Some sheet lamination methods use low temperatures, which is advantageous because intense heating and cooling can change a material's **microstructure** and properties. Temperature changes can alter part dimensions and compromise part quality. The ability to use multiple materials in a single build efficiently is also a significant advantage of sheet lamination.



Layer thickness depends on material sheet thickness.

One significant drawback of sheet lamination is that the thickness of each part layer depends on the thickness of the material sheet. This means that **layer thickness** can only be adjusted by using a sheet of the same material with a different thickness. Designers must consider this when building **CAD** models for sheet lamination. Many sheet lamination methods also create more waste than other AM processes because the excess sheet material not used in the part is simply removed. Additionally, some basic sheet lamination methods cannot create parts with hollow recesses as easily as more advanced AM processes.

The term "sheet lamination" originally referred to **Laminated Object Manufacturing** (LOM), developed by Cubic Technologies (formerly Helisys). In traditional LOM, paper sheets from a **feedstock roll** are stacked onto a build platform. A **laser** or metal blade cuts the shapes of the part layers into each sheet. A heated roller applies pressure, low heat, and an **adhesive**, often **polyurethane** glue, to the cut sheet to bond it to the previous sheet.

Like LOM, **Selective Deposition Lamination** (SDL), a similar process, also cuts and bonds part layer shapes from material sheets laid out successively on a build platform. However, SDL only applies adhesive to specific areas on the sheet that form the layers of the actual part, rather than to the entire sheet.

Plastic Sheet Lamination (PSL) is similar to traditional LOM but uses polymer material sheets. Melting temperatures used in PSL to bond part layers are typically higher than in traditional LOM methods that use paper material. LOM, SDL, and PSL are useful for creating **non-functional prototypes** but are not used to create end-use parts.

While **LOM** is typically used for rapid prototyping, other sheet lamination methods that use ceramics, metals, and composites are commonly used to produce end-use parts.

Selective Lamination Composite Object Manufacturing (**SLCOM**) is a proprietary sheet lamination method developed by EnvisionTEC, Inc. SLCOM can create very large composite parts made from **woven fibers** of metal, ceramic, and polymer materials that contain a thermoplastic binding material. During SLCOM, an **inkjet** printer head prints wax and an adhesive in the shape of the part layer onto the material sheet. Next, a blade cuts out the part shape. A heated roller applies pressure to the part layer that melts the thermoplastic, binding the sheet to the previous layer before a new material sheet is stacked on top. This process repeats until the part is complete.

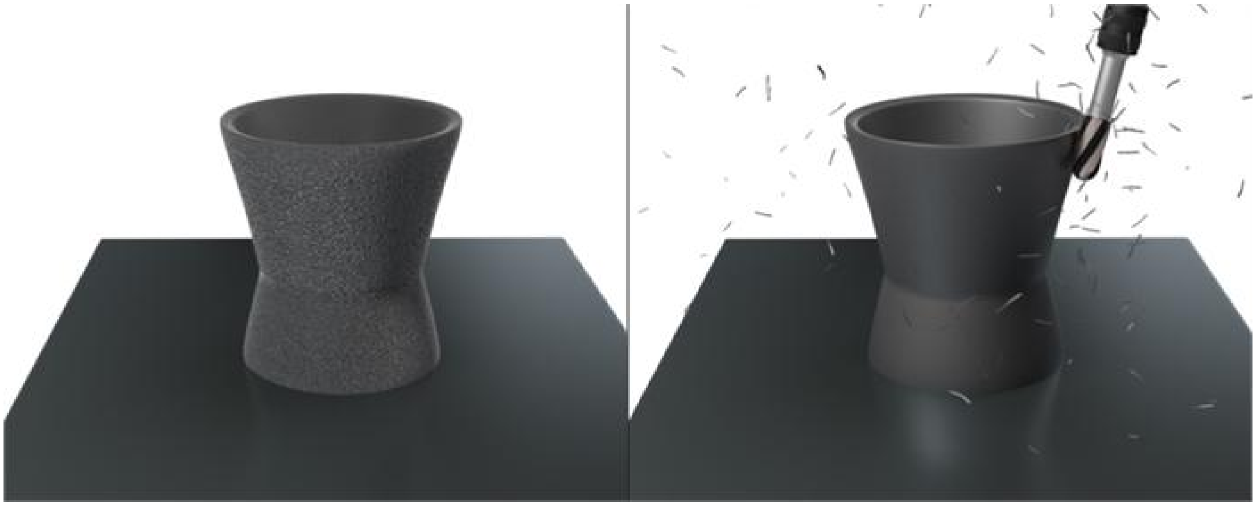
Composite-Based Additive Manufacturing (CBAM), developed by Impossible Objects Inc., can also print composites made from different combinations of ceramic, metal, and polymer fibers. Like SLCOM, CBAM uses an inkjet to print part features on material sheets. However, instead of an adhesive, CBAM applies a layer of **powdered** polymer material that sticks to the ink. Once all layers are complete, CBAM uses heat and compression to melt the polymer powder and fuse the layers into a solid part. CBAM can build parts from a wide range of materials, including **polyetheretherketone** (PEEK) and nylon, but may require post-processing to remove excess powder.

Computer-Aided Manufacturing of Laminated Engineering Materials (**CAM-LEM**), developed by CAM-LEM, Inc., can also build ceramic and metal parts, as well as composite parts. Unlike SLCOM and CBAM, the CAM-LEM process cuts each layer of the part separately with a laser before stacking and bonding all the layers together. This method allows excess material to be removed throughout the build process instead of when the part is complete. It also improves the accuracy and bonding strength of each separate layer throughout the build process. Each separately cut layer is lined with an adhesive. Finally, a **heat treatment** process melts away the adhesive and fuses the sliced layers into a solid part.

The most common sheet lamination method for producing metal parts is **Ultrasonic Additive Manufacturing** (UAM), or **Ultrasonic Consolidation**, which was developed by Fabrisonic. UAM uses **ultrasonic** waves transmitted through a **sonotrode** to bond sheets of metal tape together. The sheets of metal tape used in UAM are narrower than the material sheets used in other sheet lamination methods like SLCOM or **CBAM**.

During UAM, the vibration of the waves creates friction that bonds the metal tape to the surface of a build plate or an existing part when pressure and a small amount of heat are applied. UAM machines use metal cutting tools, such as **end mills** and **drills**, to machine the features and dimensions of each layer to CAD model specifications. Since the ultrasonic waves can bond material together using friction between the materials' surfaces, UAM does not require intense heat to bond metal surfaces together.

In general, all additive manufacturing processes require some type of **post-processing**. However, different AM process may require different post-processing methods.



Post-processing improves part accuracy and ensures material integrity

Sheet lamination uses subtractive manufacturing methods throughout the build process but may also require subtractive manufacturing after the build is complete. One reason subtractive post-processes are needed is because sheet lamination builds parts at lower **resolution** than other AM methods. This means manufacturers must build a part slightly larger than specified in the CAD model, then machine it down to the measurement **specifications**. Once machined to spec, parts made with sheet lamination also require **abrasive finishing** tools to produce a quality surface and bring parts into **tolerance**. Abrasive finishing processes use tools such as **power sanders** and **grinders**.

In addition, sheet lamination processes that use intense heat typically require heat treatment to control cooling rates since rapid temperature changes alter a part's microstructure, which could alter mechanical properties and damage or ruin a part. Sheet lamination processes that require heat treatment include CBAM, CAM-LEM, and **PSL**.

320: Setup for FDM

Fused deposition modeling (FDM), also known as **fused filament fabrication** (FFF), is one technique in a larger group of **additive manufacturing** (AM) methods referred to as material extrusion. FDM machines use a nozzle to dispense melted part material onto a build platform. Because material extrusion processes build a part layer by layer, they are commonly associated with the term **3D printing**.

The FDM process is used in small desktop hobbyist, or consumer-level, machines as well as industrial-level machines with a large **build area**. Desktop FDM machines typically work better for low volume tasks such as **rapid prototyping**, which enables an engineer to quickly create several prototypes in a short time period. In contrast, industrial FDM machines generally work better for **end-use** parts or products, which rely on repeatable, consistent results for each production run.

An important process in industrial FDM printing is **setup**, which focuses on preparation, changeover, and adjustment of the FDM machine during production. Preparation for FDM can include gathering and organizing materials to enable an efficient printing. Changeover typically involves switching materials, which can require cleaning and preheating that may lead to longer downtimes in production if done incorrectly. Adjustment in FDM printing might involve changing the temperature of the extrusion head or the speed of the print to ensure part accuracy. Although often a time-consuming process, proper setup can prevent costly errors and increase production efficiency.

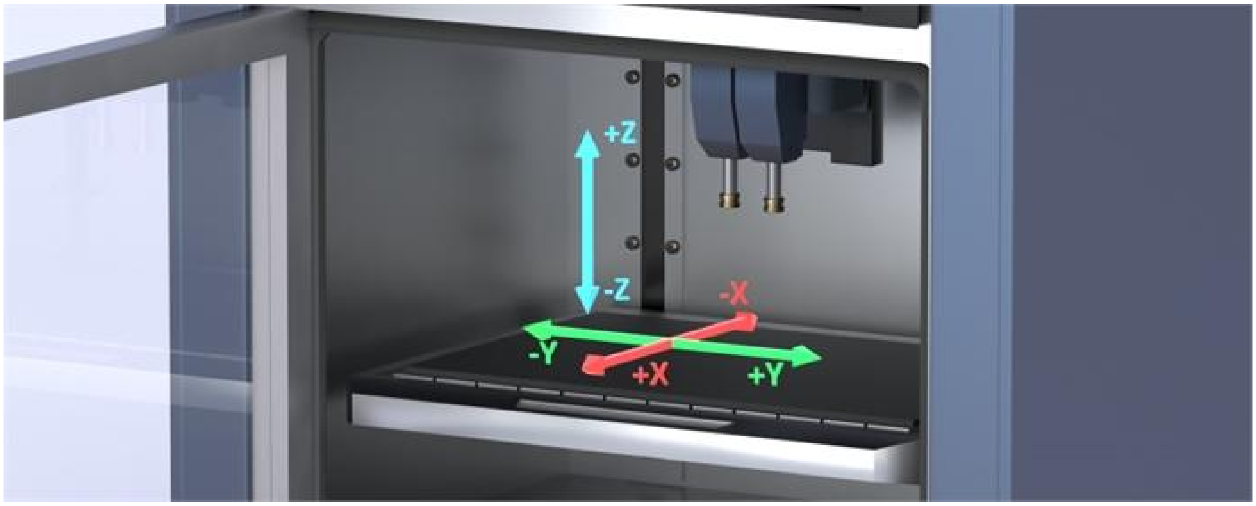
An increasing number of **FDM** machines use digital networks and software to connect to the **Industrial Internet of Things** (IIoT), a manufacturing-specific segment of internet-connected machines that includes computers and routers as well as machine tools.

FDM machines that connect to the IIoT can directly send and receive **data** without human intervention, which is known as **machine-to-machine** (M2M) communication. Monitoring the machines through the IIoT can help monitor prints and detect errors, which an operator can catch in real time during part production. This can help minimize waste associated with cost and time.

Like other **AM** methods, engineers using FDM machines work with software, often **computer-aided design** (CAD), to create a 3D design file of a part. The CAD design file is a digital representation of the physical part, but FDM machines cannot directly read design files. Because of this, an engineer or designer must convert the 3D design file into an STL format file, one of the most widely used file formats for 3D printing. The STL format uses a sequence of triangles to approximate the 3D model's external surface.

Digital slicer software takes the STL file information and “slices” it, or translates it into the layers. Many FDM machines will already have the slicer software installed. Slicer software takes the layer information and creates **G Code**, a numerical programming language that controls the functions and motions of the FDM hardware. When setting up a job for an industrial FDM machine, it may build many different parts in the same build. However, the material, layer thickness, and nozzle parameters need to be the same for all jobs.

M2M communication on the IIoT utilizes **sensors** that collect and analyze data from FDM machines and transmit it to other equipment or devices. For example, sensors can pick up unusual vibrations in the printer head or measure the speed of the material feed. The IIoT utilizes this real-time data to alert an operator to fix the vibration issue. These and other **smart manufacturing** processes generate a large amount of data.



The configuration of an FDM machine refers to the location and movements of its components. With some exceptions, most industrial size FDM printers use the **Cartesian coordinate** system to define and program the locations of machine components and part features. On these machines, configuration describes how the machine components move within the Cartesian coordinate system. FDM machines using the Cartesian coordinate system may have different mechanical designs. For example, in some FDM systems the nozzle is placed at the center of three arms. However, FDM systems are united in the way they all use three linear **axes**, labeled X, Y, and Z, to define the location of the components in physical space. The nozzle and machine table move in one or more of the axes to deposit the build materials using a rectangular grid pattern.

FDM machine manufacturers typically configure machines by programming the X,Y, and Z axes into them. The axes may align with different components on different FDM machines, depending on how the machine moves. Most FDM machines use an XY-head Z-bed configuration. This means that the machine bed moves only in the Z axis, or up-and-down, while the deposition head moves back-and-forth and left-to-right in the X and Y axes. On other machines, the components may move in different axes, or use a system other than Cartesian coordinates. For example, some printers use polar, or circular coordinates.

The basic setup operations for an industrial FDM machine revolve around three key elements: The **build chamber**, material **extruder**, and the build surface.

The build chamber of an FDM machine, which is also referred to as an oven, locks to control the temperature of the part build. The type of materials used in a build determine the correct temperature of the build chamber. Opening the chamber door during an FDM operation or cool-down will alter the temperature and may affect the part build. To avoid part defects, FDM machines lock the chamber until the production cycle completes.

The extruder melts and dispenses build and support material. The extruder assembly includes material feedlines, which feed the raw material to the extruder head, material canisters, which contain the raw build or support material, and nozzle tips, which precisely direct and dispense material during the build. Without regular cleaning during setup and maintenance, the material feedlines, canisters, and nozzle tips may clog during a print.

The build surface is the flat physical surface upon which the FDM machine builds the part. Build surfaces for industrial FDM typically utilize either a **build sheet** or **build tray**, which sit above the flat, built-in surface of the machine called the **platen**. A debris chute or purge chute often collects excess waste from the build surface and the extruder areas. Depending on the machine type, waste collected from the **purge chute** is generally deposited in the **purge bucket** or the bottom of the build chamber.

FDM machines typically need calibration after daily maintenance or any material changes, which means that calibration is part of both daily maintenance and setup for any new job build. **Calibration** is the process of ensuring the accuracy of a machine's components and movements. For an FDM machine, an operator needs to verify the X,Y, Z axes and the flatness of the build surface.

The extruder of an FDM machine has at least one nozzle that deposits build material, referred to as the model head, and at least one nozzle that deposits support material, referred to as the support head. Running a test print, or calibration print, enables an operator to manually inspect the ability of the machine to print to design specifications. Manually inspecting the test part for errors will help to detect any issues with the alignment of the model head and support head.

For three axis FDM machines, the calibration process is mostly automated. To confirm calibration, an operator should run a test print, or calibration job, of the part near the center of the platen before performing the full part run. Afterwards, an operator will need to manually inspect the test part using a **magnification** device.

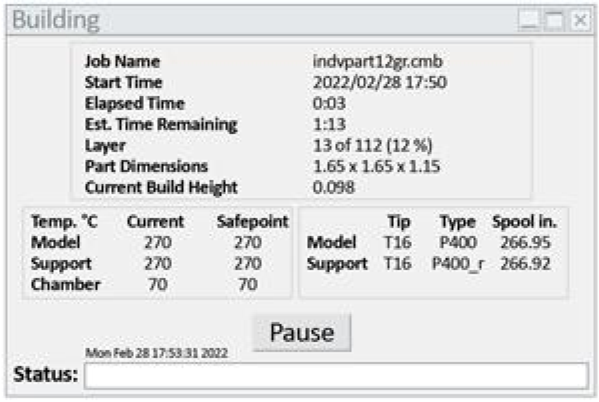
To inspect the calibration job, first verify that the machine has correctly aligned the support material with the build material. Then, verify that the machine deposited the materials in the right locations along the X and Y axes. If not, it may be necessary to adjust the **offset** value for the print head or build surface. Offsets are numerical values stored in the FDM control that reposition machine components to the correct location for a specific part run. Some FDM machines will print the offset values directly on the calibration print.

After determining that the test part is within parameters in the X and Y axes, measure and verify the calibration part's thickness, or **Z axis**, using a **caliper** or **micrometer**. Additionally, it is important to also calibrate support material. If the machine misaligns the support material during calibration, it could cause it to sag and affect the part's support material measurement.

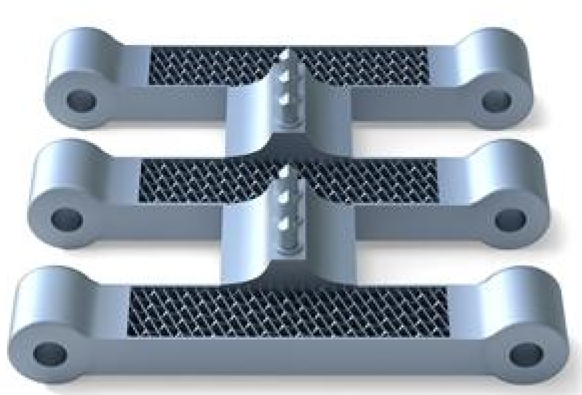
Other factors that may affect calibration can include the material type and the distance of the extrusion tip from the platen. For example, if maintenance personnel must exchange material tips, proper calibration will include updating the tip offset. This ensures that the new tip will begin at the precise height.

After calibrating the machine, an engineer or operator must arrange the software, or configure the software settings, to ensure that the **job file** is compatible with the machine's digital slicing software system settings. For example, it is important to confirm that the material loaded in the machine matches the material type designated in the job file. During the configuration process, an operator can also verify other basic information, such as the material amount needed, layer heights, and the tip size of the extruder. An operator may also need to delete previous jobs in the queue on the machine's hard drive to avoid accidentally printing the wrong file.

After configuring the settings, an operator will typically need to confirm the external and internal parameters of the part build. Internal parameters include the interior of the part, which may or may not include a fill pattern. For example, by using **lightweighting** techniques, an engineer can design a part with a **lattice structure** interior that retains the same strength as a solid interior, but uses less material and prints faster. Visible parameters include build layer thickness, or layer height, of the part. For instance, selecting a larger layer height may increase print time without sacrificing part quality.

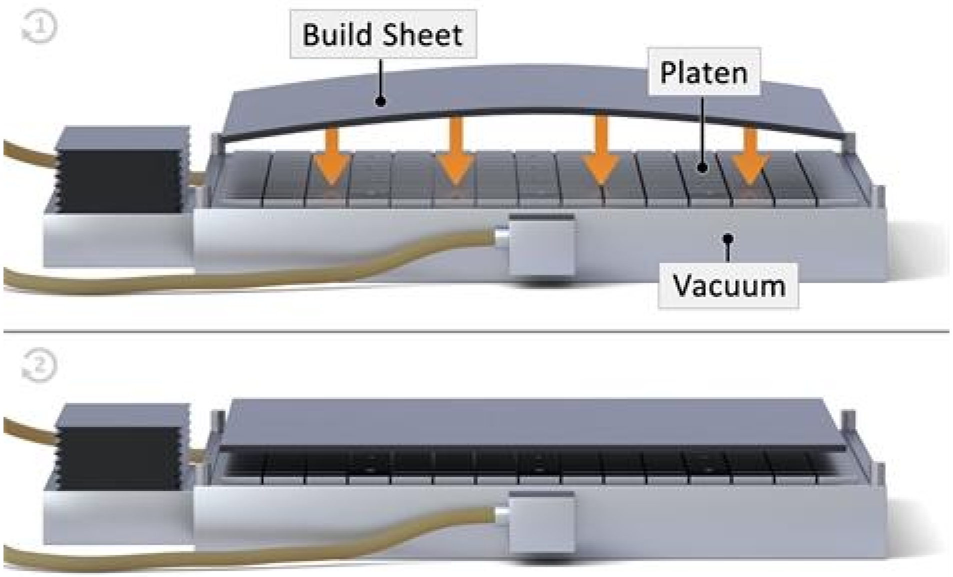


Example of a Job File



Lattice Structure

Pre-processing for the build surface is an important part of FDM setup. Pre-processing generally includes utilizing items that protect the build surface and facilitates part removal after a build, such as build sheets and build trays.



Some FDM machine build surfaces contain a **vacuum**, which holds items in place using air pressure. These build surfaces utilize a **platen**. A platen's surface contains holes or grooves that enable the vacuum's lower air pressure to pass through it, which allows it to securely hold a build sheet. A build sheet is a thin piece of material that rests on the platen in the build chamber. Other FDM machines contain a solid build tray, rather than a vacuum, as the build surface. Machines that have a build tray surface might utilize a disposable build plate, which is similar to a build sheet but is thicker and more rigid.

The purpose of the build sheet or plate is to provide a flat surface that a part can temporarily adhere to during the part build, rather than adhering to the build surface itself. Build sheets and plates can also act as a buffer layer to help prevent any dirt or debris within the machine from affecting the final part dimensions. Additionally, they can help prevent wear and tear to the build surface during part removal.

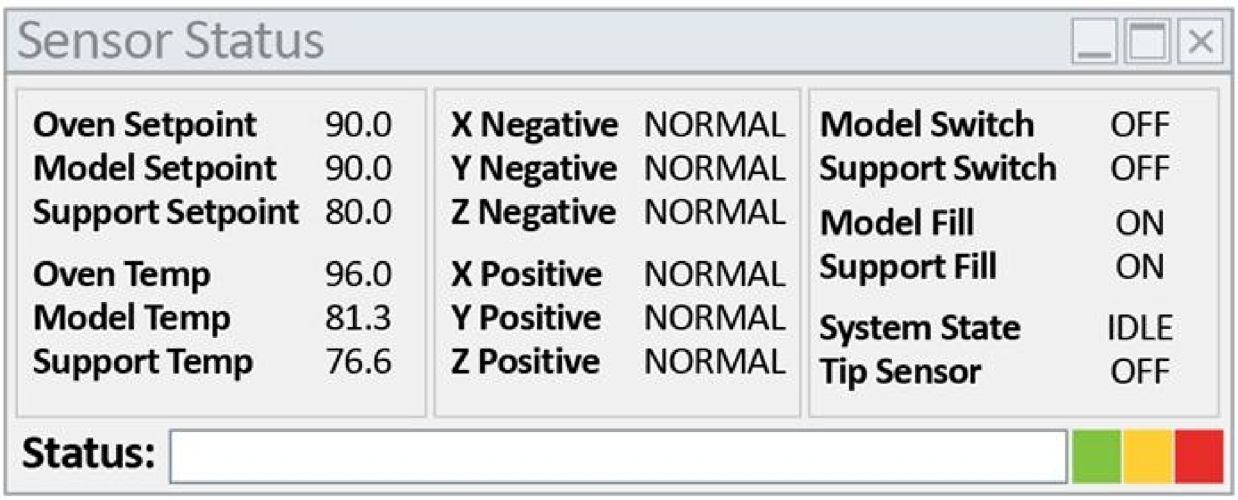
First, examine the **material canisters** to make sure that they are loaded correctly and contain the material specified for the job build. Although it may vary by machine, typically the machine will create an alarm on the display screen if the material does not match the job build instructions. However, operators should also check the job sheet and part specifications to confirm the material. In addition, verify that the cold parts of the support material and part material are loaded tightly to the hot part of the extruder. Any air gaps may cause a defect in the part build.

Next, examine the extruder nozzles, which are a critical part of an FDM printer's ability to create an accurate part. Nozzles can clog, which causes material to extrude incorrectly and create inaccurate part dimensions. Even a slightly dirty nozzle can affect the quality of a print, so they must remain free of any debris or material. For example, even if the lower part of the nozzle appears clean, a **hot-end jam** may occur near the upper part of the nozzle. In addition, a nozzle may start off clean but accidentally pick up material while depositing a layer, which may affect part quality.

Additionally, check the purge bucket before each job build and empty it if needed. The purge bucket, typically located under the automatic cleaning assembly in the heated build chamber, collects waste and debris from print jobs and routine maintenance.

Finally, before starting or resuming any building operation, verify that the build chamber has reached optimal temperature. On some FDM machines, it may take up to four hours to reach optimal building temperature.

After setting up the build chamber, an operator should perform additional tasks before starting an FDM print operation. These tasks include checking sensor status, which give an operator key information to many of the complicated processes that go into industrial FDM printing.



For example, sensors can confirm the oven and material temperatures, vacuum status, motor status, and extruder tip conditions, among other variables that may occur during a job build. Maintaining accurate sensors helps ensure repeatability during FDM part builds for end-use production.

When a sensor detects an issue with the FDM machine's functionality, it will create an alarm to alert operators and maintenance personnel. A common alarm that may occur during the beginning of a print may involve incorrect vacuum pressure, which can result from a build sheet placed improperly on the platen or debris in the vacuum line. Another problem can involve improper material loading. Before restarting the print, make sure the proper amount of time has passed for the extruder to heat the material.

After completing the job build, an operator will need to open the door of the FDM machine and remove the build tray or sheet from the heated chamber with the part still attached. Removing the part while it is still in the build chamber may damage the platen. Some FDM machines can reuse build sheets or trays for some job builds. However, it is generally advisable to install a new build sheet or tray with each job build. For example, a reused build sheet may contain material residue from the previous print, which may affect the new print or damage the platen if turned over.

For some materials, an FDM machine may perform an automatic or extended cooling period after the job build. However, some build materials, such as **Polyphenylsulfone** (PPSF), detach more easily while the build tray or sheet is still hot. For these materials, an operator should remove the build sheet from the heated chamber as soon as possible. If a part does not detach easily, the operator may need to use a **scraper** device to carefully separate the part from the build sheet. When removing the build sheet, an operator should take care to wear the proper **personal protective equipment** (PPE), which should include leather gloves and goggles.

Build Sheet

Personal Protective Equipment (PPE)

321: Maintenance for FDM

Fused deposition modeling (FDM) is an **additive manufacturing** (AM) technique also known as **fused filament fabrication** (FFF). Like most **material extrusion** processes, FDM machines use a nozzle to dispense melted part material onto a build platform. FDM is the most common AM process for hobbyists and others outside of the manufacturing industry, who often refer to AM as 3D printing. As a result, many people associate FDM with the term 3D printing.

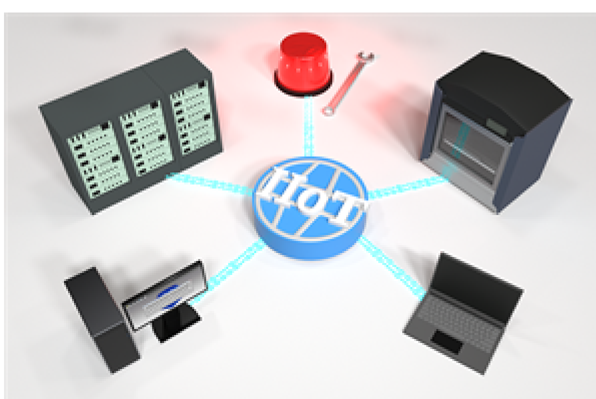
FDM machines are typically split into two categories. Small desktop hobbyist, or consumer-level, machines make up the first category. In a manufacturing setting, engineers typically use desktop FDM machines for low volume tasks such as **rapid prototyping**, which enables an engineer to quickly create several prototypes in a short time period. Industrial-level machines with large build areas make up the second category. In a manufacturing setting, industrial FDM machines do work more suited for end-use parts or products, which often require machines to produce at a large volume with a high degree of repeatability.

An important process in industrial FDM printing is **maintenance**, which helps reduce machine breakdowns and ensure user safety. Maintenance can include tasks such as adjusting or replacing components. In addition, a proper maintenance schedule for FDM machines includes monitoring equipment and updating **software**.

An increasing number of **FDM** machines are part of the **Industrial Internet of Things** (IIoT), which describes a manufacturing-specific segment of internet-connected equipment and machine tools.

FDM operators use the IIoT to assist with different maintenance approaches, which includes any activity that contributes to the care and upkeep of machines or equipment. While outdated maintenance approaches can involve fixing a machine after it breaks down, the IIoT can assist in scheduling or even predicting ongoing care and upkeep of machines and equipment.

FDM machines that connect to the IIoT can directly send and receive **data** without human intervention, which is known as **machine-to-machine** (M2M) communication. M2M communication on the IIoT utilizes **sensors** that collect and analyze data from FDM machines and transmit it to other equipment or devices. Monitoring the machines through the IIoT can help monitor prints and detect errors, which an operator can catch in real time. For example, sensors can pick up unusual vibrations in the printer head or measure the speed of the material feed. These and other **smart manufacturing** processes generate a large amount of data, which can help personnel perform planned and preventative maintenance and help avoid unscheduled downtime due to machine breakdowns.



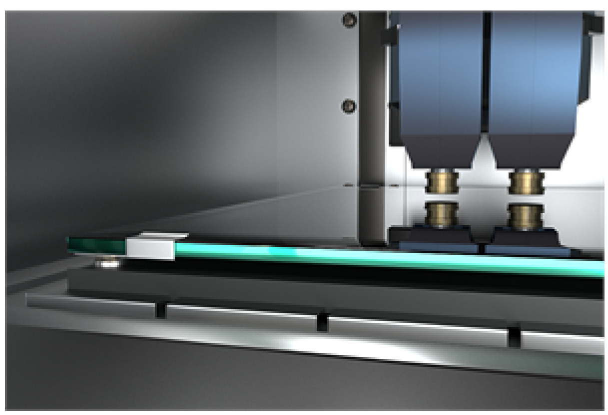
IIoT can assist with maintenance.

FDM machines can use M2M to connect to the IIoT.

A manufacturer's goals will often determine their maintenance approach. For example, a company may work on a strict schedule and want to avoid any machine breakdowns. Environment can also affect maintenance approaches, as FDM machines may operate differently in a colder or warmer environment.

Preventative maintenance approaches can prevent breakdowns by performing actions to equipment while it is in working order. **Preventative maintenance** (PM) describes the practice of performing maintenance functions on a working machine to avoid potential breakdowns. Common PM tasks for FDM include inspecting the **axes**, performing **nozzle** care, and checking the build surface. PM can often extend the life of an FDM machine and prevent long downtimes.

Planned maintenance is a type of preventative maintenance performed purposely and regularly to prevent machine deterioration or breakdown. Planned maintenance tasks for FDM machines include nozzle replacement, software updates, and detailed cleaning. Typically, the machine's age will determine the planned maintenance schedule. **Predictive maintenance** approaches involve collecting data related to an FDM machine operation in order to service a machine before maintenance issues arise. A predictive maintenance approach performs maintenance on a scheduled basis in order to prevent unscheduled downtime.



Preventative maintenance includes inspecting working machines.

Planned maintenance helps prevent breakdowns from worn parts.

Preventative and predictive maintenance approaches keep production equipment operating in the best condition possible. The basic maintenance operations for an industrial FDM machine revolve around three key elements: The **build chamber**, material **extruder**, and the build area.

Understanding how machine components work together can help operators identify when an FDM machine is not functioning properly. The build chamber of an FDM machine, also referred to as an oven, locks to control the temperature of the part build. The type of materials used in a build determine the correct build chamber temperature. Opening the chamber door during an FDM operation or cool-down will alter the temperature and may affect the part build. To avoid a defective part, an FDM machine will lock the chamber until the production cycle completes.

Performing maintenance operations on even the smallest components can help reduce downtime. For example, the extruder assembly includes material feedlines, which feed the raw material to the extruder head; material canisters, which contain the raw build or support material; and nozzle tips, which precisely direct and dispense material during the build. Without regular maintenance, the material feedlines, canisters, and nozzle tips may clog during a print. A clog would not only prevent the machine from dispensing part material, but would require maintenance staff to open the oven door mid-build to clear the clog. This would likely cause the part to be scrapped.

The build surface is a critical maintenance area. The build surface is the flat physical surface upon which the FDM machine builds the part, and industrial FDM machines typically utilize either a **platen** or **build tray** system. A debris chute or **purge chute** often collects excess waste from the build surface and the extruder areas. Depending on the machine type, waste collected from the purge chute is generally deposited on the bottom of the build chamber or in a **purge bucket**.

A regular maintenance routine for FDM machines includes updating system software, which personnel can typically update through a **web browser** or electronic storage devices such as a **USB drive**. Any internet-based system updates to the FDM machine controller should come directly from a secure online portal or control center provided by the **original equipment manufacturer** (OEM). Similarly, any USB or other storage devices should come directly from the FDM OEM and contain file formats compatible to the machine's system at the time it was built.

System updates can include updating controller software, which can offer fixes if a software-related problem develops with the internal control. In addition to repair, control software upgrades can enable an FDM machine to print with new materials that were not previously available.

Regularly checking for and installing software updates and upgrades can also help fix known vulnerabilities. Failing to perform regular system updates can leave systems open to preventable **cyber attacks**, a term used to describe any attempt by a malicious actor to harm or illegally access a digital system. Cyber attacks may come from within an organization or from external sources. Many cyber attacks involve illegal, unauthorized attempts by hackers to gain access to a system, disrupt or disable a network, or harm or delete digital files. In some cases, USB or devices that come from sources other than the OEM may also pose a security risk. Manufacturing organizations should document and take steps to resolve all potential cybersecurity risks related to FDM maintenance.

Daily maintenance on FDM machines can help reduce equipment damage, which can result in costly downtime and repairs.

Any daily maintenance routine for FDM machines should include cleaning the build surface. To clean the surface, first remove the build sheet or tray and turn off the vacuum. Next, use a soft brush to remove any debris that has fallen into the platen's **canals**. Finally, check the vacuum ports to ensure that they are not clogged, as obstructed vacuum ports can affect how the build sheet holds to the platen during a job build.

Another key part of daily maintenance includes emptying the purge bucket, which catches material cleaned from the FDM **liquefier** and tips. This is especially important with multi-material printers, which use multiple types of build or support material and generate more waste than single material printers. Cleaning also prevents contamination of the part with debris from the previous build material. Since the purge bucket is typically located inside the heated chamber, always wear the proper **personal protective equipment** (PPE) to prevent burns.

In addition to daily maintenance, it is important to perform a regular schedule of ongoing maintenance tasks to keep an FDM machine from breaking down. Ongoing maintenance may include cleaning the chamber door, lamps, and touchscreen display. Manufacturers may schedule maintenance on weekly, monthly, and **quarterly** intervals, or they may prefer to schedule using the number of hours that the machine operates.

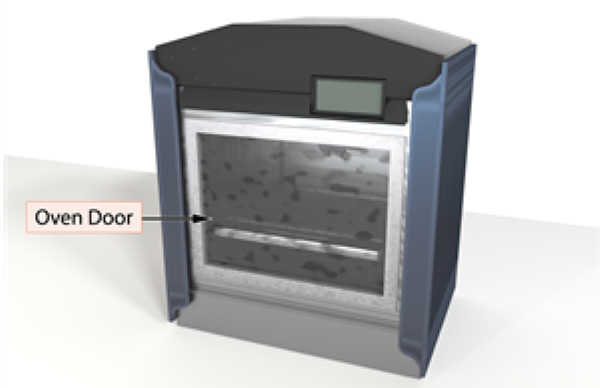
Every week, or about every 500 hours of operation, clean and inspect the tip wipe assembly, including the purge ledge. If the purge assembly has any marks, surface blemishes, or other signs of damage, it may need to be replaced.

In FDM machines, a small piece of metal, referred to as a wiper, helps remove excess material during the build cycle. Inspect the wiper weekly, or every 500 hours. If a wiper is misaligned or worn, it may have a significant impact on a job build. The top edge of the wiper should be straight and free from any notching or dents. If it is damaged, replace it.

Brushes work with the wiper assembly and will also need to be inspected every week or 500 hours. Like the wiper, replace the brushes if any notches from wear appear on their tips or across the top.

Maintenance personnel should perform some tasks as needed, rather than on a schedule. For example, the chamber door and other exterior system components will eventually become dirty. Clean them with mild soap and water or other commercially available cleaning products that are safe for plastic. In addition, smudges and dirt may build up on the control, which will also need cleaning to prevent unnecessary wear. Avoid abrasive or alkaline cleaners, which may damage the FDM machine.

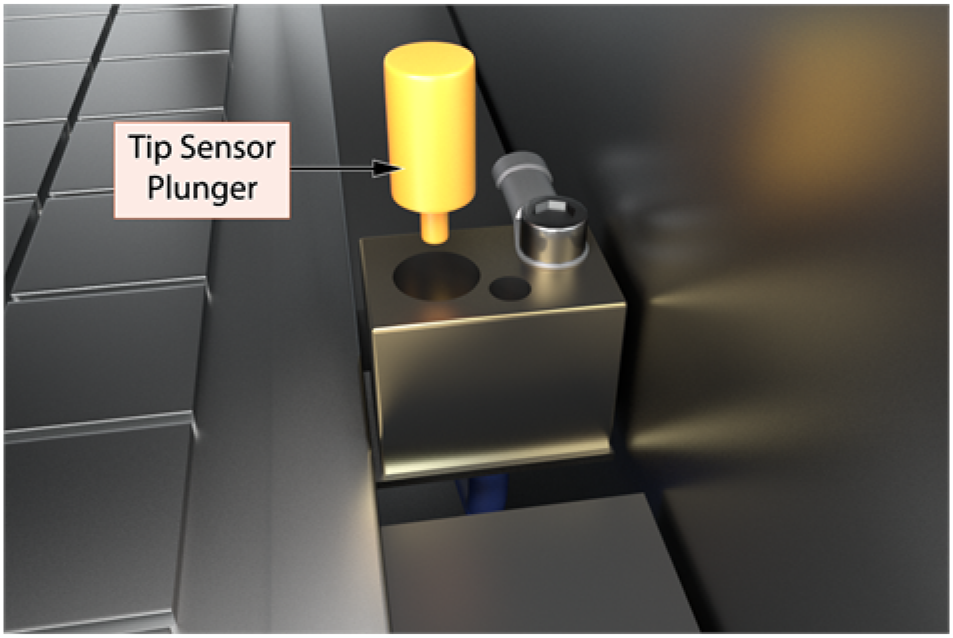
As-needed maintenance includes upgrading software, which an FDM machine typically does by USB drive upload or network update. In some cases, IIoT-enabled FDM machines will receive updates automatically. In many cases, upgrading software will erase files in the job queue of the FDM machine, so an operator may need to resend print jobs after the update completes.



Clean oven door as needed to remove dirt.

As-needed maintenance includes software upgrades.

Though many FDM maintenance tasks are universal, other tasks will vary according to the machine brand and its usage. In addition to FDM machines varying from one **OEM** to another, factors such as the amount that it is used and the build material type will affect the type and amount of maintenance a machine requires. For example, after extended usage an operator should inspect the tip sensor plunger for material residue. Any residue can be removed with a razor blade or similar sharp object.



In addition to general guidelines, it is important for all maintenance staff to become familiar with the specific duties required for the FDM machines in their facility. Each machine model has a manual that will list the specific machine components and recommended maintenance. Maintenance personnel should consult the manual, which in addition to printed hard copy can typically be found online through the manufacturer's support center. However, it is also important to consult a supervisor or manager for any further best practices.

Daily Maintenance	As-Needed Maintenance	Weekly Maintenance
Clean build surface ✥	✓ Clean exterior controls ✥	Check purge edge for marks ✥
Unclog vacuum ports ✥	Install software updates ✥	Remove material from sensor plunger ✥
✓ Empty purge buckets ✥	Clean chamber door ✥	✓ Inspect wiper ✥