

Additive Manufacturing BME741A



A T M E
College of Engineering



DEPARTMENT OF MECHANICAL ENGINEERING

Module-1 **Introduction, Development, Basics, Process in AM**

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AM EVOLUTION

- Initially, AM was used specifically to create visualization models for products as they being developed.
- Later, Models were employed to supply information on “3 Fs”
- **Form:** Models appreciated the shape and general purpose of design fully.
- **Fit:** With improved accuracy, components were built to the tolerances required for assembly purposes.
- **Function:** With improved material properties, parts were assessed according to how they would eventually work.

RAPID PROTOTYPING

- Rapid Prototyping (RP) is a process used for rapidly creating a part, usually a prototype or basis model from which the further models and eventually the final product will be derived.
- The term Rapid Prototyping is inadequate and does not effectively describe more recent applications of the technology.
- Many parts are now directly manufactured from RP machines. Hence it is not possible to label them as just “prototypes”
- The term also overlooks the basic principle from which the parts are fabricated. i.e., additive approach.
- Because of these reasons the terminology has essentially evolved from Rapid Prototyping to **Additive Manufacturing**.

ADDITIVE MANUFACTURING (AM)

- The basic principle of this technology is that a model, initially generated using a 3-D CAD system, can be directly fabricated without the need for process planning.
- In AM, parts are made by adding materials in layers; each layer is a thin cross-section of the part derived from the original CAD data.
- The thinner each layer is, the closer the final part will be to original.

Distinction between AM & CNC Machining

- AM shares some of its DNA with CNC Machining technology.
- Just like AM, CNC is also a computer based technology.
- CNC primarily works on principle of subtractive process to manufacture products rather than additive one.
- The knowledge of the differences between the two processes is important, to understand how each of them may be implemented for different stages in product development process or for different types of product.

Distinction between AM and CNC Machining

Sl. No	Particulars	AM	CNC Machining
1	Material	It is originally developed around polymeric materials, waxes and paper laminates. AM parts may have voids or anisotropy based on how the design was input to the machine.	It works particularly well for hard, relatively brittle materials like steels and other metal alloys. CNC parts will normally be more homogeneous and predictable in quality.
2	Speed	To make a part in an AM machine, it may only take a few hours AM technology can be used to produce a part in a single stage.	Using CNC machining, this same process may take weeks CNC is likely to be a multistage manufacturing process, which requires considerable setup and process planning.
3	Complexity	Complexity in geometry of a part like undercuts and internal features can be easily built.	Some geometrical features cannot be fabricated, as there may be certain accessibility constraints which prevents tool from being located on part surface.
4	Accuracy	Accuracy in build plane is determined by the positioning of build mechanism, which will normally involves gearboxes and motors of some kind.	The accuracy in CNC machines is mainly determined by similar positioning resolution along the axes and by the diameter of the rotary cutting tools.
5	Geometry	AM machines break a complex 3D problem into a series of simple 2D cross-sections with normal thickness. Continuity in complex parts can be created by creating close proximity of one cross- section with adjacent one.	In CNC, machining of surfaces is normally generated in 3D space. Complex geometries like undercuts, enclosures, sharp internal corners becomes extremely difficult to produce if these features are beyond certain limit.
6	Programming	Part will not be built very well if the programming is not done properly.	Incorrect programming could result in severe damage to the machine.

Reasons Why You Need to Consider Design for Additive Manufacturing

1. Create parts with greater complexity

Additive manufacturing can overcome the limitations of traditional manufacturing methods to create highly complex parts with improved functionality.

One example is the traditional manufacture of injection moulds: here, cooling channels are typically straight, leading to a slower and less consistent cooling of a moulded part. In contrast, with 3D printing the cooling channels can be re-designed to create more complex or curved shapes, providing more homogeneous heat transfer. This results in improved cooling characteristics, helping to produce higher quality parts whilst prolonging the service life of a mould.



Reasons Why You Need to Consider Design for Additive Manufacturing

2. Minimal material waste

With the new design possibilities afforded by 3D printing, engineers can produce lightweight parts in part by optimising the distribution of material, leading to substantial material savings.

This can be achieved in part thanks to advanced software like [topology optimisation](#), and tools like generative design and lattice structures. Based on mathematical calculations, topology optimisation can help to analyse the best shape for a part and remove unnecessary material without compromising the structural integrity of the part. Using traditional (subtractive) methods, this material would simply be cut away

Coupled with 3D printing, generative design and topology optimisation software are already used by industrial giants like [Siemens](#) and [General Motors](#). While Siemens used generative design software to develop its 3D printed gas turbine blades, General Motors aims to reduce the weight of a vehicle by exploring various options for material distribution within a component.

Reasons Why You Need to Consider Design for Additive Manufacturing

3. Simplified assembly

Part consolidation is another game-changing design benefit of additive manufacturing. With traditional manufacturing, multiple components must be produced and then subsequently assembled to create the final part.

However, with 3D printing, several smaller components can be integrated into a single custom part during the design stage, allowing you to print the entire part at once. This significantly simplifies the assembly process, and can even eliminate the need for assembly at times. In addition to this, a consolidated part eliminates the need for procuring and storing any additional subcomponents or spare parts, ultimately reducing inventory and maintenance costs.

Reasons Why You Need to Consider Design for Additive Manufacturing

4. Material innovation

Advancements in materials research have led to the exciting development of new materials. Consequently, unique 3D printing materials have been developed that would be difficult to machine or mould, such as TPU filaments and metal superalloys powders). Or take for example [3D printing with high-performance thermoplastics](#), developed specifically for engineering applications. In some cases, these high-performance materials can even substitute metal parts, providing a lightweight, cost-saving alternative.

Therefore, when designing a part for 3D printing, engineers can explore new options that offer better material properties, such as thermal conductivity or malleability. In addition to this, 3D printing gives an opportunity to design parts with [multi-material properties](#) (e.g. rigidity and flexibility) or integrated insulating and conductive properties.

Reasons Why You Need to Consider Design for Additive Manufacturing

5. Cost-effective customization

3D printing enables quick and multiple design iterations at no extra cost, taking customisation possibilities to new heights. And as additive manufacturing creates parts directly from digital files, the manufacturing process is significantly accelerated. This means that companies can produce customised products much faster and cost-effectively.

Customised designs will enable mass customisation across industries, from consumer goods to medical and automotive. For example, in the medical industry, mass customisation is already revealing itself in the 3D printed devices, tailored to the needs of the patient. Such devices range from individualised braces and prosthetics to surgical guides and hearing aids, designed to perfectly match patient's anatomy.

Reasons Why You Need to Consider Design for Additive Manufacturing

6. Minimum support structures

Part orientation is one of the key benefits when designing for additive manufacturing. Choosing the correct part orientation during the design stage can reduce the printing and post-processing time whilst minimising the need for supports. In spite of the fact that support structures are virtually a necessity for many complex 3D printed parts, it is ideal to design parts with as few supports as possible, as this will make post-processing easier, saving you time and material.

While there is no a one-size-fits-all solution when it comes to minimising the number of supports used, with careful design a part can often be orientated and optimised to carry itself whilst using a minimum amount of support structures, saving post-processing time.

Looking ahead, as [automation trends](#) take hold in the AM industry, part orientation, as well as supports, could be automatically generated with a new generation of AM software.

Advantages of Additive Manufacturing:

Speed: The rapid character of the technology is not only about the time it takes to build parts but also it enhances the whole product development process.

Ease of Data Conversion: Since 3D CAD is being used as the starting point and the transfer to AM is relatively seamless, there is much less concern over data interpretation.

Reduction of Process Steps: Regardless of the complexity of parts to be built, building within an AM machine is generally performed in a single step.

Reduction in Process Time: Irrespective of the complexity of the product, added features the time required for manufacturing is less compared to CNC Manufacturing.

Reduction in Cost: Since the process is carried out in a single step, the process brings down manufacturing cost to minimum compared to conventional manufacturing processes.

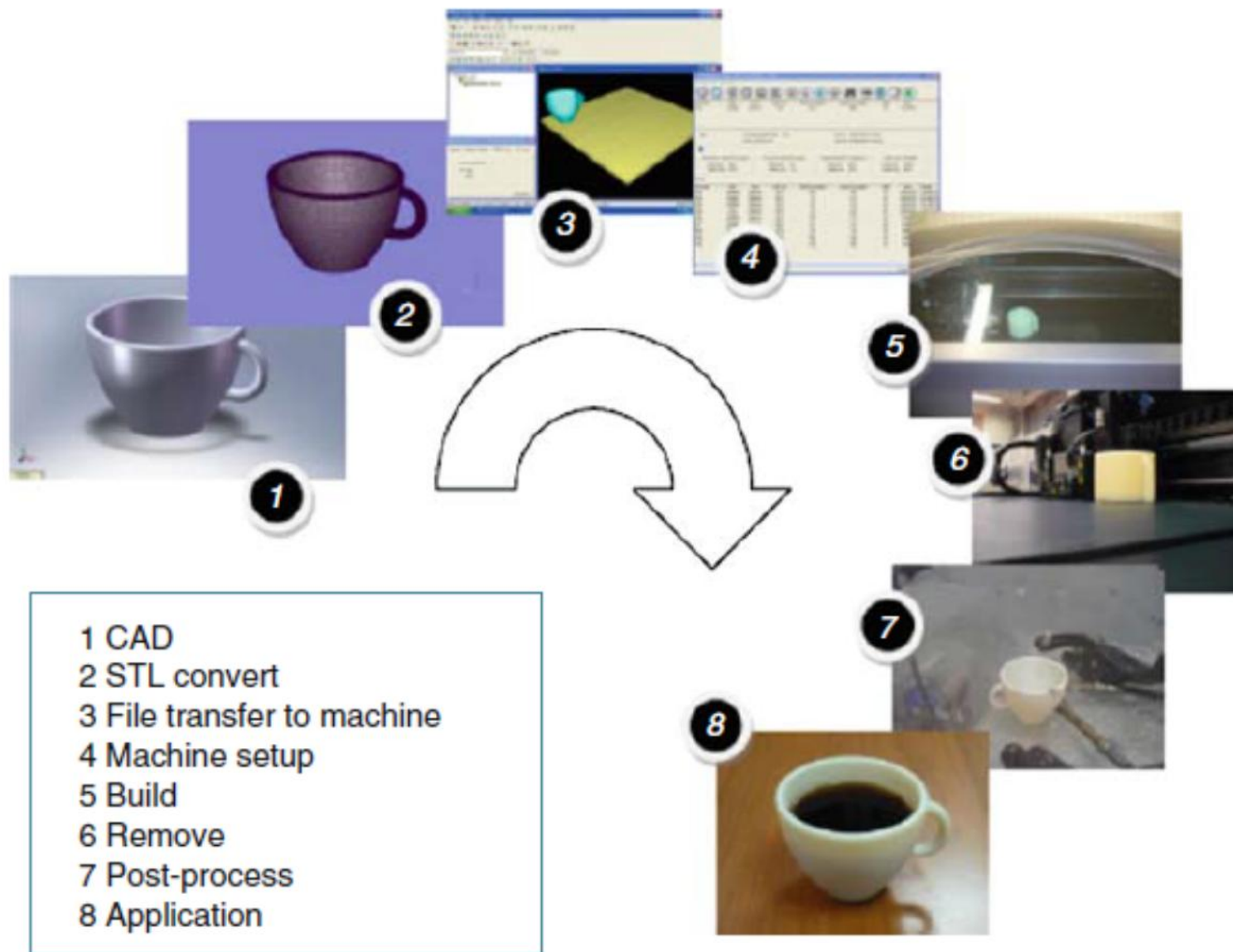
Wide Range of Application: With some supporting technologies it can be possible to manufacture a vast range of parts with different characteristics.

Generic AM Process Chain:

AM involves a number of steps that move from the virtual CAD description to the physical resultant part.

- Step 1: Conceptualization and CAD
- Step 2: Conversion to STL
- Step 3: Transfer to AM Machine and STL File Manipulation
- Step 4: Machine Setup
- Step 5: Build
- Step 6: Removal
- Step 7: Postprocessing
- Step 8: Application





Generic AM Process Chain:

Step 1: Conceptualization and CAD

- The first step in product development process is to come up with a idea of how the product will look and perform.
- Conceptualization takes many forms from textual and narrative descriptions to sketches and representative models.
- In AM, product description will be in the form that allows a physical model to be made.
- The AM process therefore start with 3D CAD information.
- The 3D source data can be created by computer user, using user-interface or via **reverse engineering technologies**.

Generic AM Process Chain:

Step 2: Conversion to STL

- Every AM machine accepts the STL file format, and every CAD system can output such a file format.
- The term STL is derived from StereoLithography, which is the first commercial AM technology from 3D systems.
- The file describes the external closed surfaces of the original CAD model and forms the basis for calculation of slices.

Generic AM Process Chain:

Step 3: Transfer to AM Machine and STL file Manipulation

- The STL file describing the part is then transferred to the AM machine.
- Here some general manipulation to the file is done in order to correct size, position and orientation for building.
- AM system software normally has a visualization tool that allows the user to view and manipulate the part.
- It is quite common to build more than one part in an AM machine. This may be multiples of same part or completely different STL files.

Generic AM Process Chain:

Step 4: Machine Setup

- The AM machine will be properly setup prior to the build process.
- The settings includes the build parameters like material constraints, energy source, layer thickness, timings etc.
- The setup parameters will be specific to a machine or process being used.
- Some machines will have very few setup changes while others provide a variety of parameters to choose and optimize the process.

Generic AM Process Chain:

Step 5: Build

- Building the part is mainly an automated process and machine can carry out the process without supervision.
- Only superficial monitoring is done to ensure no errors have taken place like running out of material, power or software glitches.

Generic AM Process Chain:

Step 6: Removal and Cleanup

- Once the AM machine has completed the build, the parts are separated from the build platform
- At this time it is necessary to ensure that the operating temperatures are sufficiently low and there are no actively moving parts.
- Sometimes the parts produced still requires significant amount of manual finishing before they are ready to use.
- This cleanup stage is also considered as the initial part of post-processing stage.

Generic AM Process Chain:

Step 7: Postprocessing

- Once removed from the machine, the parts may be weak at this stage or may have supporting structures to be removed for application purposes.
- This may involve abrasive finishing like polishing, sandpapering or application of coatings.
- This stage in the process is application specific. Some requires minimum of post-processing while other applications need careful handling to maintain good precision and finish.
- This stage is primarily a manual task due to the complexity of AM parts.

Generic AM Process Chain:

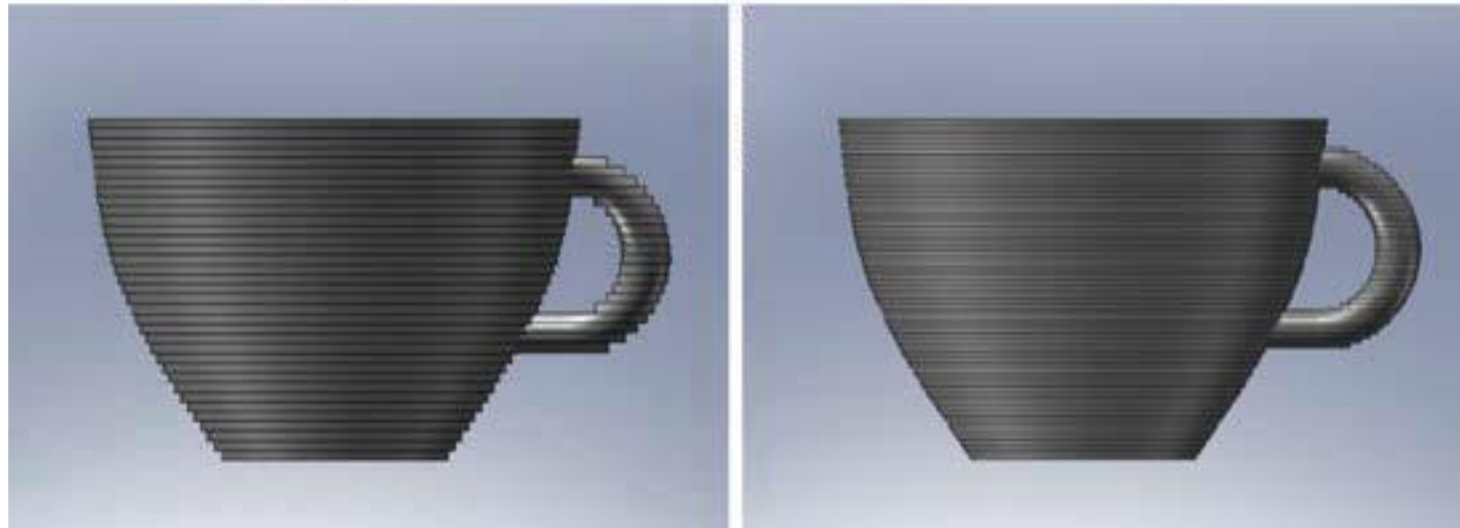
Step 8: Application

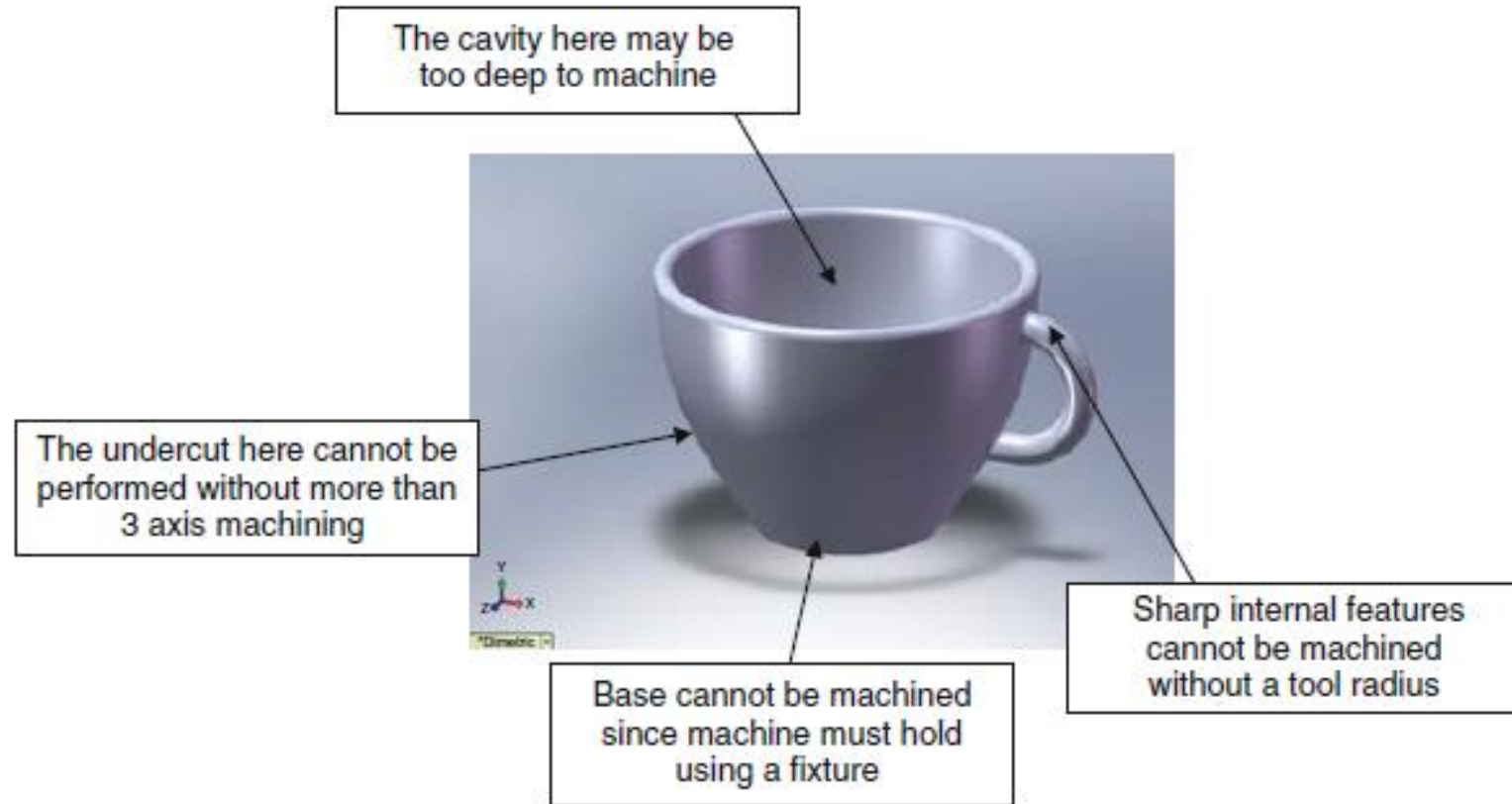
- Parts at this stage will be ready to use, with some prior additional treatment like painting to give an acceptable surface texture and finish.
- More the finishing requirements, more are the laborious and lengthy will be the treatments.
- They may also be required to be assembled together with other mechanical or electronic components to form a final model or product.
- Although parts may be made from similar materials to those available from other manufacturing processes, parts may not behave according to standard material specifications.

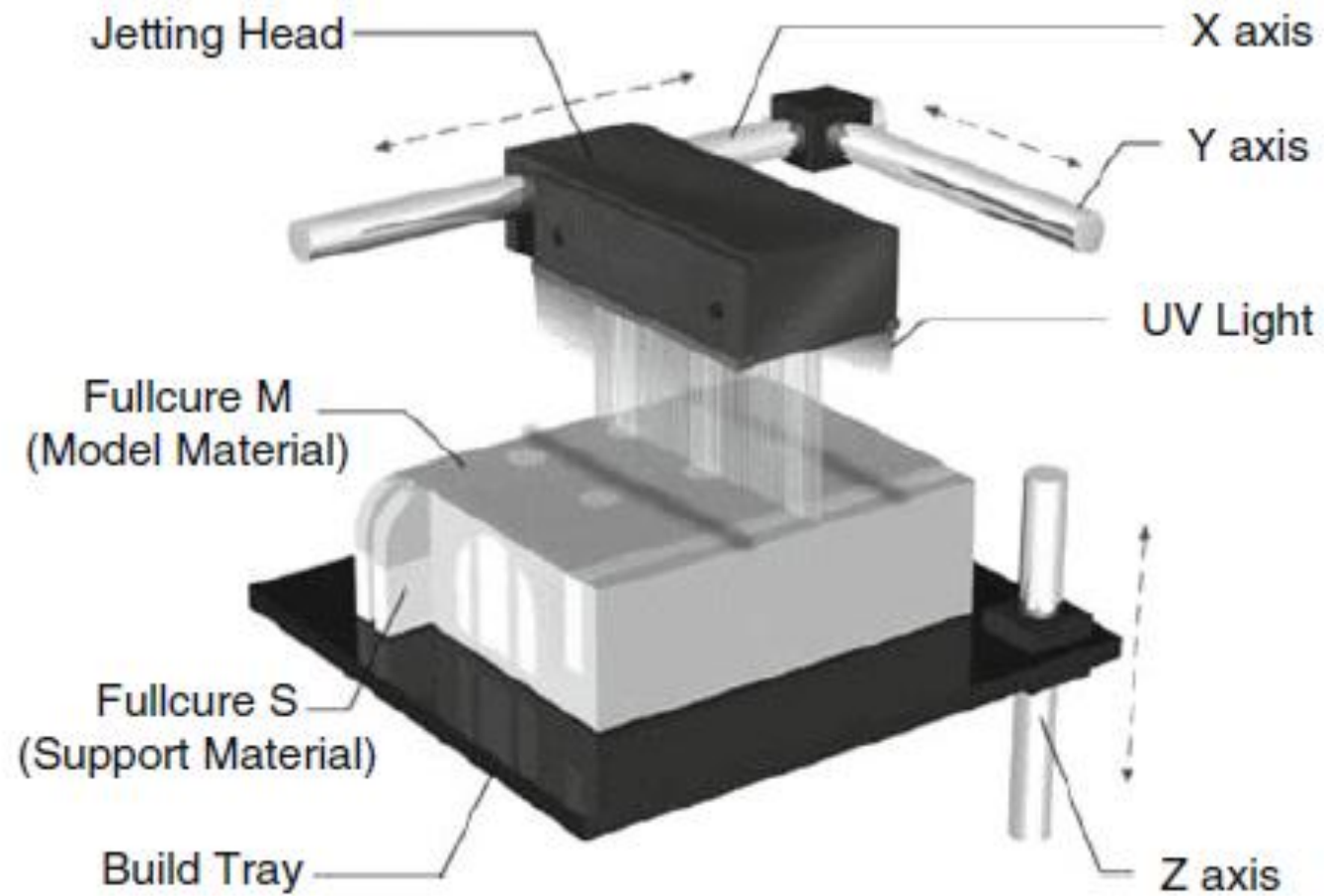
Computer-Aided Design Technology



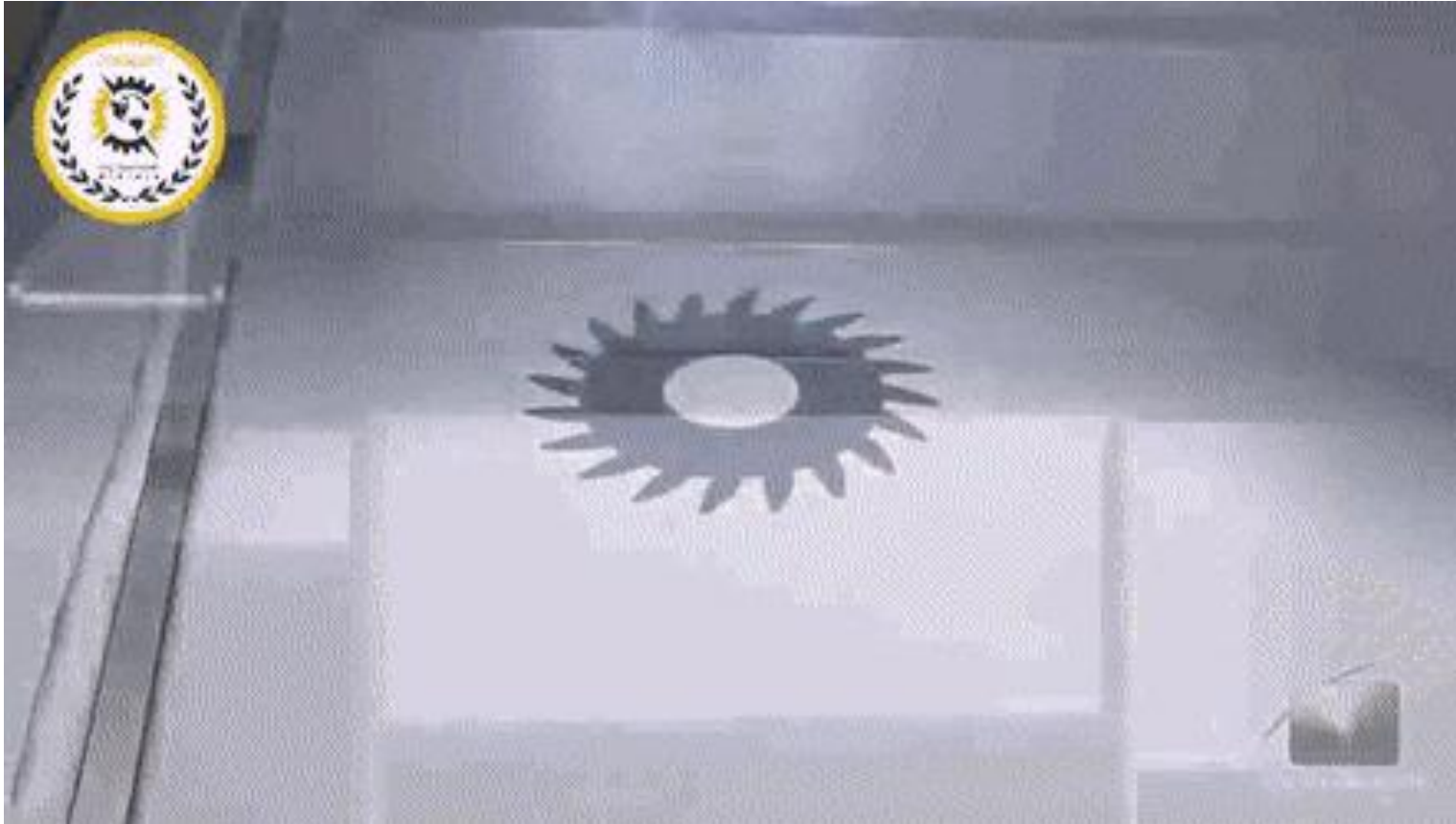
A CAD model on the left converted into STL format on the right

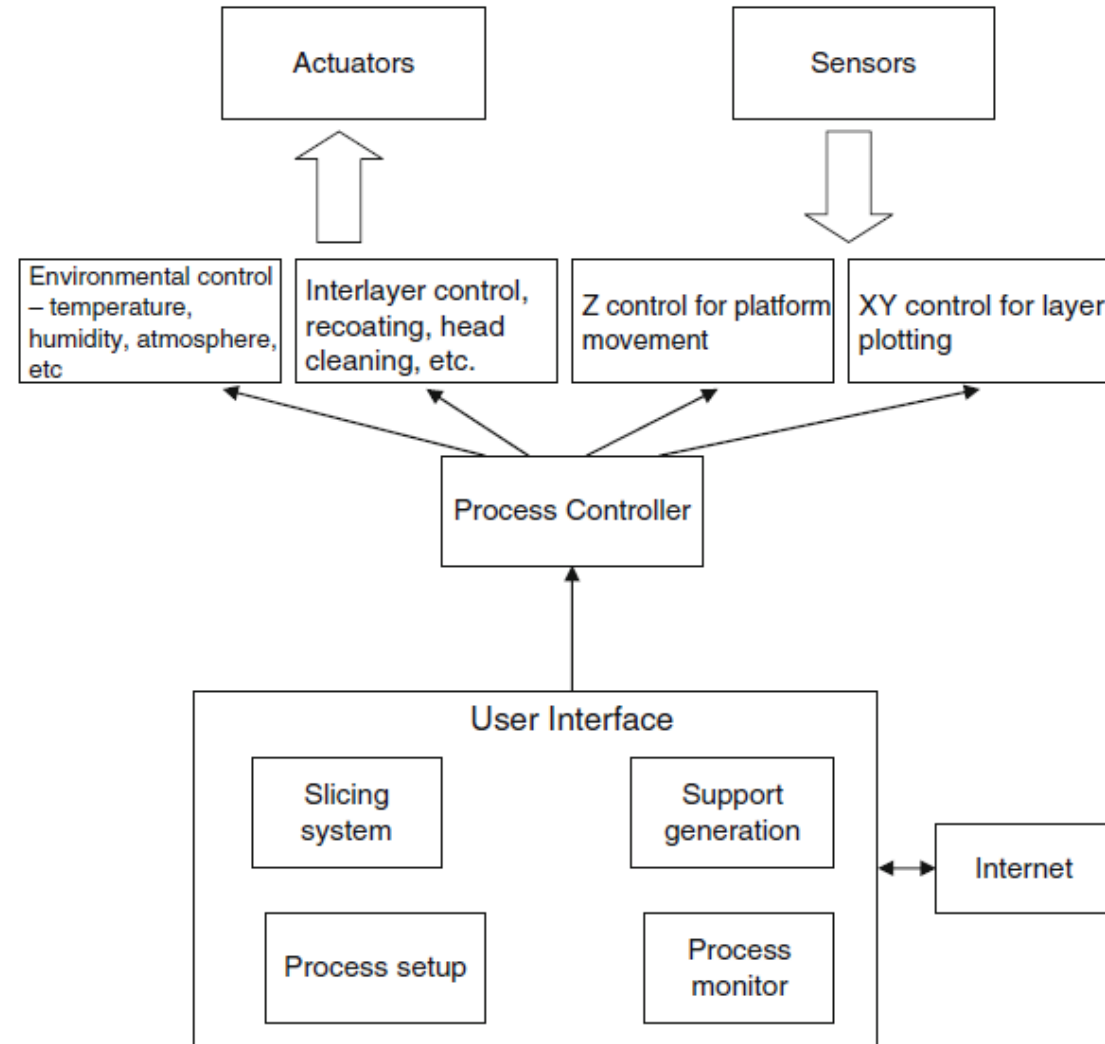






Printer technology used on an AM machine (photo courtesy of Objet)

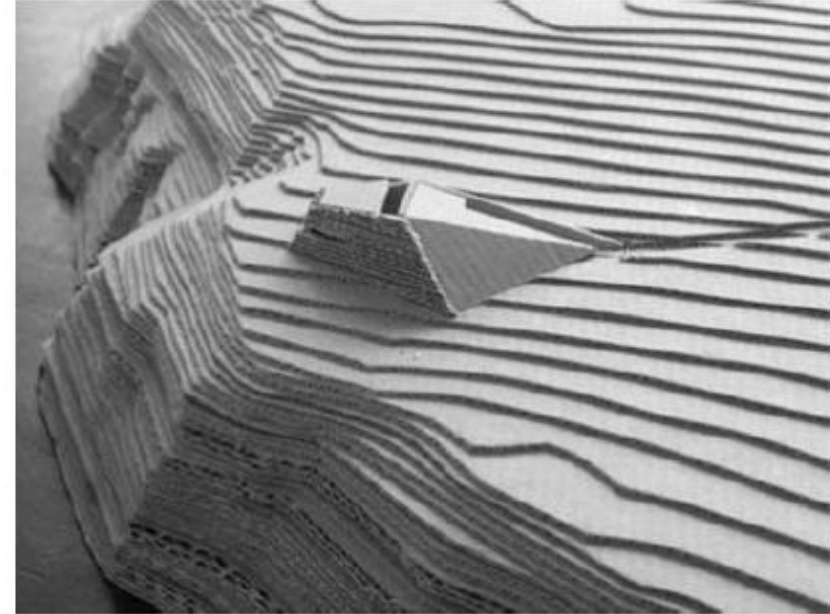




General integration of an AM machine

The Use of Layers

- A key enabling principle of AM part manufacture is the use of layers as finite 2D cross-sections of the 3D model.
- Almost every AM technology builds parts using layers of material added together; and certainly all commercial systems work that way, primarily due to the simplification of building 3D objects.
- Using 2D representations to represent cross-sections of a more complex 3D feature has been used in many applications outside AM.
- The most obvious example of this is how cartographers use a line of constant height to represent hills and other geographical reliefs.



An architectural landscape model, illustrating the use of layers
(photo courtesy of LiD)



designed model

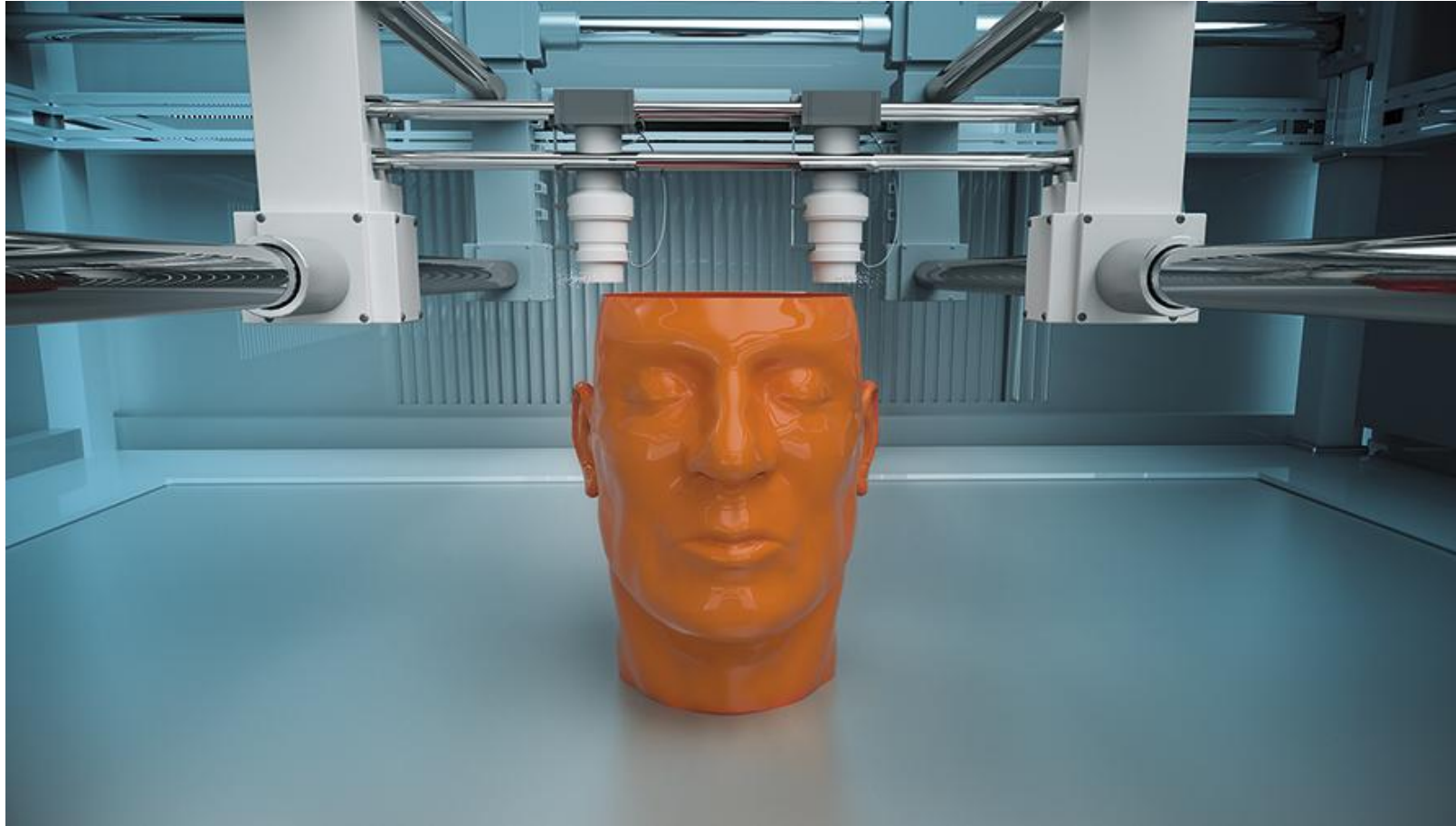


fabricated object
(layer thickness $2h$)

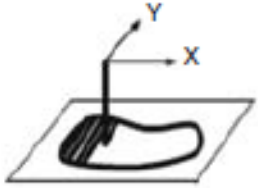
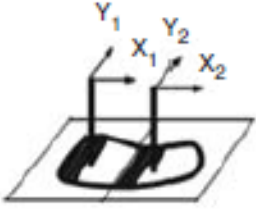
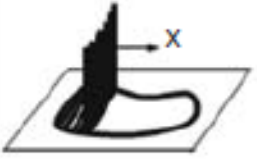
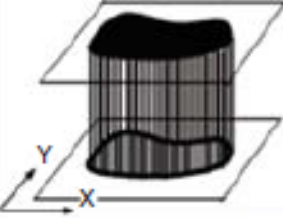


fabricated object
(layer thickness h)

The Use of Layers



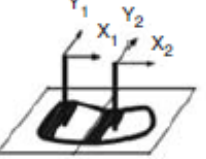
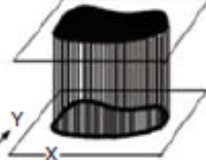
Classification of AM Processes

	1D Channel 	2x1D Channels 	Array of 1D Channels 	2D Channel 
Liquid Polymer	SLA (3D Sys)	Dual beam SLA (3D Sys)	Objet	Envisiontech MicroTEC
Discrete Particles	SLS (3D Sys), LST (EOS), LENS Phenix, SDM	LST (EOS)	3D Printing	DPS
Molten Mat.	FDM, Solidscape		ThermoJet	
Solid Sheets	Solido PLT (KIRA)			

Layered Manufacturing (LM) processes as classified by Pham (note that this diagram has been amended to include some recent AM technologies)

Classification of AM Processes.....

- The first dimension relates to the method by which the layers are constructed.
- Earlier technologies used a single point source to draw across the surface of the base material. Later systems increased the number of sources to increase the throughput, which was made possible with the use of droplet deposition technology
- For example, which can be constructed into a one dimensional array of deposition heads. Further throughput improvements are possible with the use of 2D array technology using the likes of **Digital Micro-mirror Devices (DMDs)** and high resolution display technology, capable of exposing an entire surface in a single pass.

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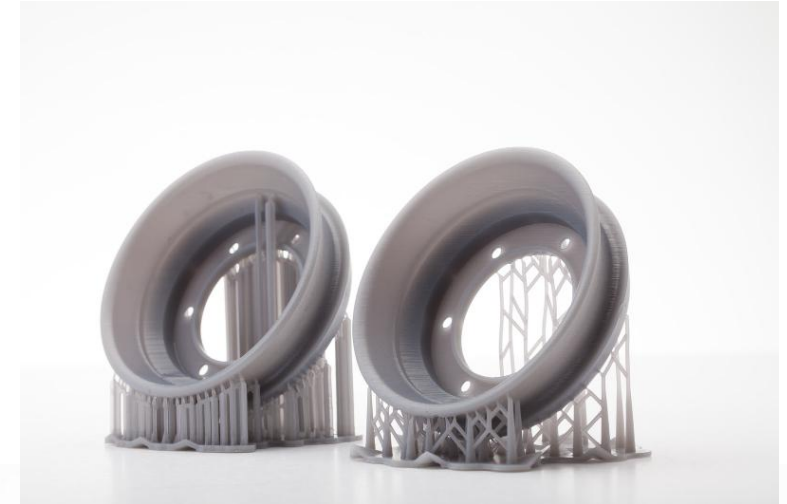
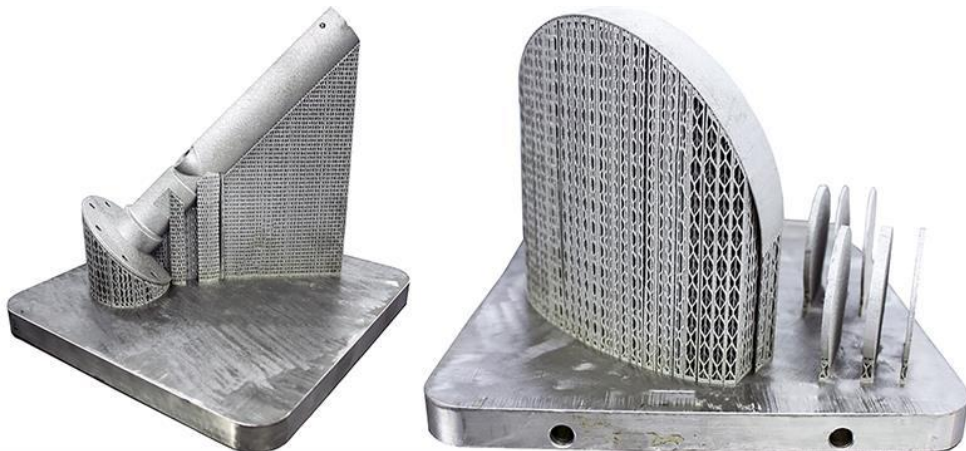
Classification of AM Processes:

AM Technologies can be classified in numerous ways:

1. According to Baseline technology, like whether process uses lasers, printer technology, extrusion technology etc.
2. According to type of raw material input
 - Liquid polymer
 - Discrete particles
 - Molten material
 - Laminated sheets

Removal of Supports

- Wherever the supports meet the part there will be small marks and reducing the amount of supports would make the part more accurate and reduce the amount of part cleanup and post-process finishing.
- Parts that require supports may also require planning for their removal. Supports may be located in difficult to reach regions within the part. For example, a hollow cylinder with end caps built vertically will require supports for the top surface



Metal Systems

1. The Use of Substrates:

- Most metal systems make use of a base platform or substrate onto which parts are built and from which they must be removed using machining, wire cutting, or a similar method.
- The need to attach the parts to a base platform is mainly because of the high temperature gradients between the temporarily molten material and its surroundings.
- If the material did not adhere to a solid platform then there would be a tendency for the part to warp as it cools, which means further layers of powder cannot be spread evenly.
- Therefore, even though these are mainly powder-based systems, there is still a need for supports.

2. Energy Density

- The energy requirements for melting metals to over 1,000°C is obviously much higher than heating polymers to around 200°C.
- Heat shielding, insulation, temperature control, and atmospheric control are much more stringent than in the lower cost polymer systems.

3. Weight

- Metal powder systems may process lightweight titanium powders but they also process high-density tool steels.
- The powder handling technology must be capable of withstanding the mass of these materials.
- This means that power requirements for positioning and handling equipment must be quite substantial or gear ratios must be high (and corresponding travel speeds lower) to deal with these tasks.

4. Accuracy

- Metal powder systems are generally at least as accurate as corresponding polymer powder systems.
- Surface finish is characteristically grainy but part density and part accuracy are very good.
- Surface roughness is in the order of a few tens to a few hundreds of microns depending on the process and can be likened in general appearance to precision casting technology.
- For metal parts, this is often not satisfactory and at least some shot-peening is required to smooth the surface.
- Key mating features on metal parts often require surface machining or grinding. The part density will be high (generally over 99%), although some voids may still be seen.

5. Speed

- Since there are heavy requirements on the amount of energy to melt the powder particles and to handle the powders within the machine, the build speed is generally slower than a comparable sized polymer system.
- Laser powers are not excessively high, usually just a few hundred watts (polymer systems start at around 50 watts of laser power).
- This means that the laser scanning speed is quite low to ensure enough energy is delivered to the powder.

Hybrid Systems

- Some of the machines described above are, in fact, hybrid additive/subtractive processes rather than purely additive.
- Including a subtractive component can assist in making the process more precise.
- This stage makes for a smooth planar surface onto which the next layer can be added, negating cumulative effects from errors in droplet deposition height.
- It should be noted that when subtractive methods are used, waste will be generated.
- Machining processes require removal of material that in general cannot easily be recycled.
- Similarly, many additive processes require the use of support structures and these too must be removed or “subtracted.”

Milestones in AM Development

- We can look at the historical development of AM in a variety of different ways. The origins may be difficult to properly define and there was certainly quite a lot of activity in the 1950s and 1960s, but development of the associated technology (computers, lasers, controllers, etc.) caught up with the concept in the early 1980s.
- Interestingly, parallel patents were filed in 1984 in Japan (Murutani), France (Andre et al.) and in the US (Masters in July and Hull in August).
- All of these patents described a similar concept of fabricating a 3D object by selectively adding material layer by layer.
- While earlier work in Japan is quite well-documented, proving that this concept could be realized, it was the patent by Charles Hull that is generally recognized as the most influential since it gave rise to 3D Systems.
- This was the first company to commercialize AM technology with the Stereolithography apparatus

Milestones in AM Development.....

- Further patents came along in 1986, resulting in three more companies, Helisys (Laminated Object Manufacture or LOM), Cubital (with Solid Ground Curing, SGC), and DTM with their Selective Laser Sintering (SLS) process.
- It's interesting to note neither Helisys or Cubital exist anymore, and only SLS remains as a commercial process with DTM merging with 3D Systems in 2001.
- In 1989, Scott Crump patented the Fused Deposition Modeling (FDM) process, forming the Stratasys Company. Also in 1989 a group from MIT patented the 3D Printing (3DP) process.
- These processes from 1989 are heavily used today, with FDM variants currently being the most successful.
- Rather than forming a company, the MIT group licensed the 3DP technology to a number of different companies, who applied it in different ways to form the basis for different applications of their AM technology.
- The most successful of these is ZCorp, which focuses mainly on low-cost technology.



The first AM technology from Hull, who founded 3D systems (photo courtesy of 3D Systems)

Maintenance of Equipment

- It is important to realize that many machines require careful maintenance.
- Some machines use fragile laser or printer technology that must be carefully monitored and that should preferably not be used in a dirty or noisy environment.
- Similarly, many of the feed materials require careful handling and should be used in low humidity conditions.
- While machines are designed to operate unattended, it is important to include regular checks in the maintenance schedule.
- Laser-based systems are generally expensive because of the cost of the laser itself. Furthermore, maintenance of a laser can be very expensive since the expected lifetime can be as low as 4,000 operating hours for tube lasers and up to more than 15,000 h for solid state lasers.
- Printheads are also components that have finite lifetimes for the printer-based systems.
- The fine nozzle dimensions and the use of relatively high viscosity fluids mean they are quite prone to clogging and contamination effects. Replacement costs are, however, generally quite low.

Materials Handling Issues

- In addition to the machinery, AM materials often require careful handling. The raw materials used in some AM processes have **limited shelf-life** and must also be kept in conditions that prevent them from chemical reaction or **degradation**.
- **Exposure to moisture** and to excess light should be avoided.
- Most processes use materials that can be used for more than one build. However, it may be that this could degrade the material if used many times over and therefore a procedure for maintaining **consistent material quality** through recycling should also be observed.
- While there are some **health concerns** with extended exposure to some photopolymer resins, most AM polymer raw materials are safe to handle.
- SLS powders may have **additives** that prevent degradation due to oxidation since they are kept at elevated temperatures for long periods of time.

Design for AM

Number of build-related factors when considering the setup of an AM machine

Part Orientation:

- If a cylinder was built on its end, then it would consist of a series of circular layers built on top of each other.. Additionally, as the layering process for most AM machines takes additional time, a long cylinder built vertically will take more time to build than if it is laid horizontally.
- Orientation of the part within the machine can affect part accuracy. Since many parts will have complex features along multiple axes, there may not be an ideal orientation for a particular part. Furthermore, it may be more important to maintain the geometry of some features when compared with others, so correct orientation may be a judgment call.
- In general upward-facing features in AM have the best quality. The reason for this depends upon the process. For instance, upward-facing features are not in contact with the supports required for many processes. For powder beds, the upward-facing features are smooth since they solidify against air, whereas downward-facing and sideways-facing features solidify against powder and thus have a powdery texture. For extrusion processes, upward-facing surfaces are smoothed by the extrusion tip. Thus, this upward-facing feature quality rule is one of the few rules-of-thumb that are generically applicable to every AM process.

Design for AM

Removal of Supports:

- It is a good idea to try and minimize the amount. Wherever the supports meet the part there will be small marks and reducing the amount of supports would reduce the amount of part cleanup and post-process finishing.
- Parts that require supports may also require planning for their removal. Supports may be located in difficult-to-reach regions within the part.

Hollowing Out Parts:

- A honeycomb- or truss-like internal structure can assist in providing support and strength within a part, while reducing its overall mass and volume.
- All of these approaches must be balanced against the additional time that it would take to design such a part. However, there are software systems that would allow this to be done automatically for certain types of parts.

Inclusion of Undercuts and Other Manufacturing Constraining Features:

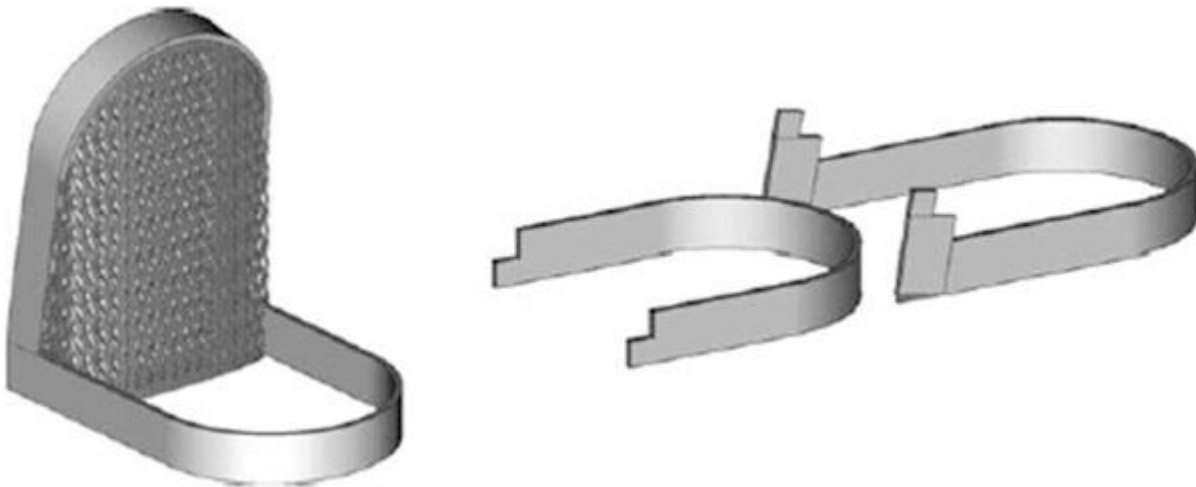
- Undercuts, draft angles, holes, pockets, etc. must be created in a specific order when using multiple-stage conventional processes. While this can be ignored when designing the part for AM, it is important not to forget them if AM is being used just as a prototype process.
- AM can be used in the design process to help determine where and what type of rib, boss, and other strengthening approaches should be used on the final part. If the final part is to be injection molded, the AM part can be used to determine the best location for the parting lines in the mold.

Design for AM

Interlocking Features:

A solution may be to break the design up into segments that can fit into the machine and manually assemble them together later.

Techniques can include incorporation of interlocking features and maximizing surface area so that adhesives can be most effective. Such regions should also be in easy-to-reach but difficult-to-observe locations.



Design for AM

Reduction of Part Count in an Assembly:

The AM process is therefore toward the end of the product development process and the design does not need to consider alternative manufacturing processes. This in turn means that if part assembly can be simplified using AM, then this should be done. For example, it is possible to build fully assembled hinge structures by providing clearance around the moving features. In addition, complex assemblies made up of multiple injection molded parts, for instance, could be built as a single component. Thus, when producing components with AM, designers should always look for ways to consolidate multiple parts into a single part and to include additional part complexity where it can improve system performance.



Design for AM

Identification Markings/Numbers

- Although AM parts are often unique, it may be difficult for a company to keep track of them when they are possibly building hundreds of parts per week.
- It is a straightforward process to include identifying features on the parts. This can be done when designing the CAD model but that may not be possible since the models may come from a third party.
- There are a number of software systems that provide tools for labeling parts by embossing alphanumeric characters onto them as 3D models.
- In addition, some service providers build all the parts ordered by a particular customer (or small parts which might otherwise get lost) within a mesh box so that they are easy to find and identify during part cleanup.

Applications

- Product development
- Data visualization
- Rapid prototyping
- Specialized manufacturing



Additive Manufacturing Applications

Aerospace

AM excels at producing parts with weight-saving, complex geometric designs. Therefore, it is often the perfect solution for creating right, strong aerospace parts.

In August 2013, NASA successfully tested an SLM-printed rocket injector during a hot fire test that generated 20,000 pounds of thrust. In 2015, the FAA cleared the first 3D-printed part for use in a commercial jet engine. CFM's LEAP engine features 19 3D-printed fuel nozzles. At the 2017 Paris Air Show, FAA-certified, Boeing 787 structural parts fabricated from titanium wire were displayed, according to Aviation Week.

Automotive

CNN reported that the McLaren racing team is using 3D-printed parts in its Formula 1 race cars. A rear wing replacement took about 10 days to produce instead of five weeks. The team has already produced more than 50 different parts using additive manufacturing. In the auto industry, AM's rapid prototyping potential garners serious interest as production parts are appearing. For example, aluminum alloys are used to produce exhaust pipes and pump parts, and polymers are used to produce bumpers.

Additive Manufacturing Applications

Healthcare

At the New York University School of Medicine, a clinical study of 300 patients will evaluate the efficacy of patient-specific, multi-colored kidney cancer models using additive manufacturing. The study will examine whether such models effectively assist surgeons with pre-operative assessments and guidance during operations.

Global medical device manufacturing company Stryker are funding a research project in Australia that will use additive manufacturing technology to create custom, on-demand 3D printed surgical implants for patients suffering from bone cancer.

In general, healthcare applications for additive manufacturing are expanding, particularly as the safety and efficacy of AM-built medical devices is established. The fabrication of one-of-a-kind synthetic organs also shows promise.

Product Development

As the potential for AM's design flexibility is realized, once impossible design concepts are now being successfully re-imagined. Additive manufacturing unleashes the creative potential of designers who can now operate free of the constraints under which they once labored.

Additive Manufacturing Materials

It is possible to use many different materials to create 3D-printed objects. AM technology fabricates jet engine parts from advanced metal alloys, and it also creates chocolate treats and other food items.

Thermoplastics

Thermoplastic polymers remain the most popular class of additive manufacturing materials. Acrylonitrile butadiene styrene (ABS), polylactic acid (PLA) and polycarbonate (PC) each offer distinct advantages in different applications. Water-soluble polyvinyl alcohol (PVA) is typically used to create temporary support structures, which are later dissolved away.

Metals

Many different metals and metal alloys are used in additive manufacturing, from precious metals like gold and silver to strategic metals like stainless steel and titanium.

Ceramics

A variety of ceramics have also been used in additive manufacturing, including zirconia, alumina and tricalcium phosphate. Also, alternate layers of powdered glass and adhesive are baked together to create entirely new classes of glass products.

Biochemicals

Biochemical healthcare applications include the use of hardened material from silicon, calcium phosphate and zinc to support bone structures as new bone growth occurs. Researchers are also exploring the use of bio-inks fabricated from stem cells to form everything from blood vessels to bladders and beyond.

Additive Manufacturing Processes

There are a variety of different additive manufacturing processes:

Powder Bed Fusion

Powder Bed Fusion (PBF) technology is used in a variety of AM processes, including direct metal laser sintering (DMLS), selective laser sintering (SLS), selective heat sintering (SHS), electron beam melting (EBM) and direct metal laser melting (DMLM). These systems use lasers, electron beams or thermal print heads to melt or partially melt ultra-fine layers of material in a three-dimensional space. As the process concludes, excess powder is blasted away from the object.

Binder Jetting

The binder jetting process is similar to material jetting, except that the print head lays down alternate layers of powdered material and a liquid binder.

Directed Energy Deposition

The process of directed energy deposition (DED) is similar to material extrusion, although it can be used with a wider variety of materials, including polymers, ceramics and metals. An electron beam gun or laser mounted on a four- or five-axis arm melts either wire or filament feedstock or powder.

Additive Manufacturing Processes

Material Extrusion

Material extrusion is one of the most well-known additive manufacturing processes. Spooled polymers are extruded, or drawn through a heated nozzle mounted on a movable arm. The nozzle moves horizontally while the bed moves vertically, allowing the melted material to be built layer after layer. Proper adhesion between layers occurs through precise temperature control or the use of chemical bonding agents.

Material Jetting

With material jetting, a print head moves back and forth, much like the head on a 2D inkjet printer. However, it typically moves on x-, y- and z-axes to create 3D objects. Layers harden as they cool or are cured by ultraviolet light.

Sheet Lamination

Laminated object manufacturing (LOM) and ultrasonic additive manufacturing (UAM) are two sheet lamination methods. LOM uses alternate layers of paper and adhesive, while UAM employs thin metal sheets conjoined through ultrasonic welding. LOM excels at creating objects ideal for visual or aesthetic modeling. UAM is a relatively low-temperature, low-energy process used with various metals, including titanium, stainless steel and aluminum.

Vat Polymerization

With vat photopolymerization, an object is created in a vat of a liquid resin photopolymer. A process called photopolymerization cures each microfine resin layer using ultraviolet (UV) light precisely directed by mirrors.

Additive Manufacturing BME741A



A T M E
College of Engineering



DEPARTMENT OF MECHANICAL ENGINEERING

Module-2

Photo-Polymerization Process

Powder Bed Fusion Process

Extrusion Based Process

Dr. Mohanakumara K C
Assistant Professor,
Dept. of Mechanical Engineering,
ATMECE, Mysuru



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Vat Photopolymerization Processes

- Photopolymerization processes make use of liquid, radiation-curable resins, or photopolymers, as their primary materials.
- Most photopolymers react to radiation in the ultraviolet (UV) range of wavelengths, but some visible light systems are used as well.
- Upon irradiation, these materials undergo a chemical reaction to become solid. This reaction is called photopolymerization, and is typically complex, involving many chemical participants.

Photopolymerization Processes

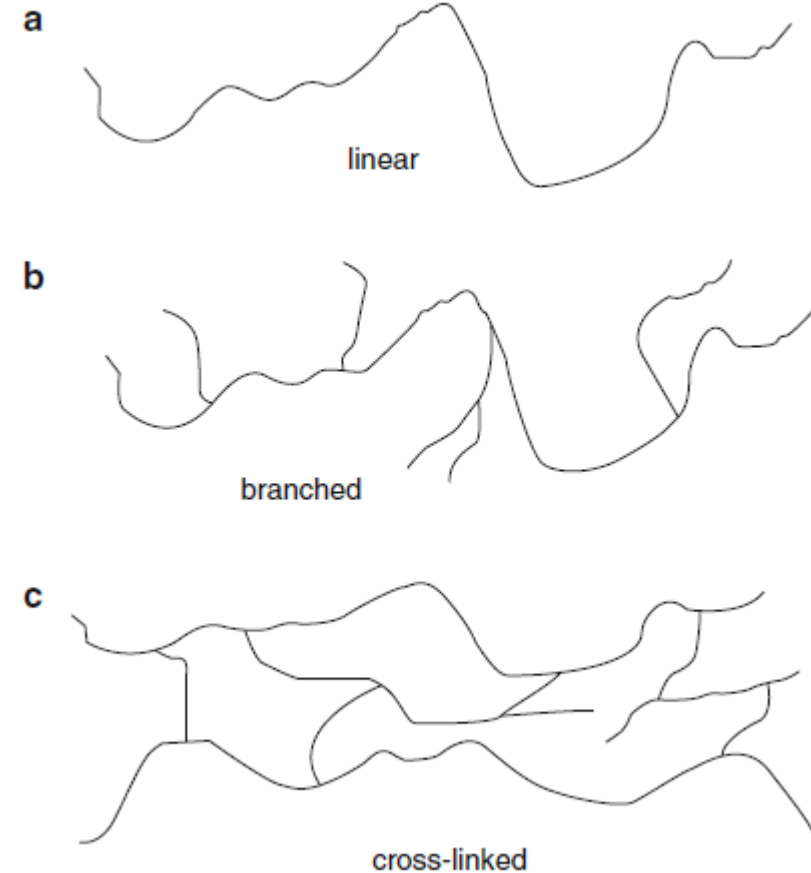
- In the mid-1980s, Charles (Chuck) Hull was experimenting with UV-curable materials by exposing them to a scanning laser, similar to the system found in laser printers.
- He discovered that solid polymer patterns could be produced. By curing one layer over a previous layer, he could fabricate a solid 3D part.
- This was the beginning of stereolithography (SL) technology. The company 3D Systems was created shortly thereafter to market SL machines as “rapid prototyping” machines to the product development industry.

Photopolymerization Processes

- ❖ Various types of radiation may be used to cure commercial photopolymers, including gamma rays, X-rays, electron beams, UV, and in some cases visible light.
- ❖ In VP systems, UV and visible light radiation are used most commonly.
- ❖ In the microelectronics industry, photomask materials are often photopolymers and are typically irradiated using far UV and electron beams. In contrast, the field of dentistry uses visible light predominantly.

Polymer Structures

- These resins were prepared from acrylates, which had high reactivity but typically produced weak parts due to the inaccuracy caused by shrinkage and curling.
- The acrylate-based resins typically could only be cured to 46 % completion when the image was transferred through the laser.
- When a fresh coating was put on the exposed layer, some radiation went through the new coating and initiated new photochemical reactions in the layer that was already partially cured.
- This layer was less susceptible to oxygen inhibition after it had been coated.
- The additional cross-linking on this layer caused extra shrinkage, which increased stresses in the layer, and caused curling that was observed either during or after the part fabrication process .



Polymer Structures

- The epoxy resins produced more accurate, harder, and stronger parts than the acrylate resins. While the polymerization of acrylate compositions leads to 5–20 % shrinkage, the ring-opening polymerization of epoxy compositions only leads to a shrinkage of 1–2 %.
- This low level of shrinkage associated with epoxy chemistry contributes to excellent adhesion and reduced tendency for flexible substrates to curl during cure.
- Furthermore, the polymerization of the epoxy-based resins is not inhibited by atmospheric oxygen.

- However, the epoxy resins have disadvantages of slow photospeed and brittleness of the cured parts.
- The acrylates are also useful to reduce the brittleness of the epoxy parts. Another disadvantage of epoxy resins is their sensitivity to humidity, which can inhibit polymerization.

- As a result, most SL resins commercially available today are epoxides with some acrylate content. It is necessary to have both materials present in the same formulation to combine the advantages of both curing types. The improvement in accuracy resulting from the use of hybrid resins has given SL a tremendous boost.

Photopolymer Chemistry

- VP photopolymers are composed of several types of ingredients: photoinitiators, reactive diluents, flexibilizers, stabilizers, and liquid monomers. Broadly speaking, when UV radiation impinges on VP resin, the photoinitiators undergo a chemical transformation and become “reactive” with the liquid monomers.
- A “reactive” photoinitiator reacts with a monomer molecule to start a polymer chain. Subsequent reactions occur to build polymer chains and then to cross-link—creation of strong covalent bonds between polymer chains.
- Polymerization is the term used to describe the process of linking small molecules (monomers) into larger molecules (polymers) composed of many monomer units. Two main types of photopolymer chemistry are commercially evident:
 - Free-radical photopolymerization—acrylate
 - Cationic photopolymerization—epoxy and vinylether

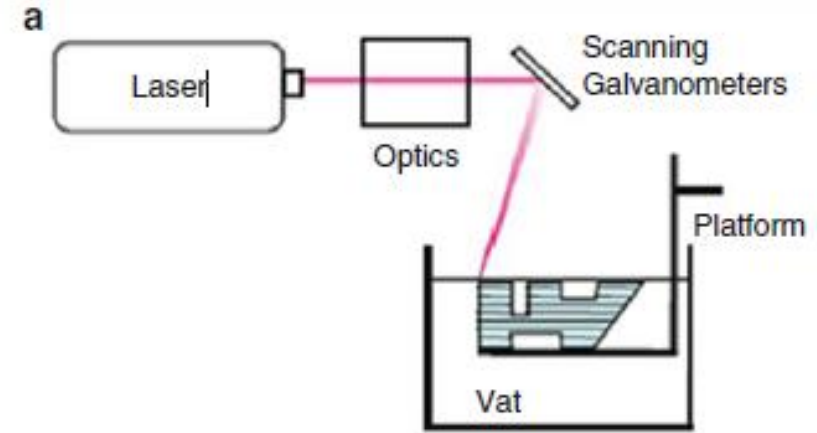
Irradiance and Exposure

As a laser beam is scanned across the resin surface, it cures a line of resin to a depth that depends on many factors. However, it is also important to consider the width of the cured line as well as its profile. The shape of the cured line depends on resin characteristics, laser energy characteristics, and the scan speed

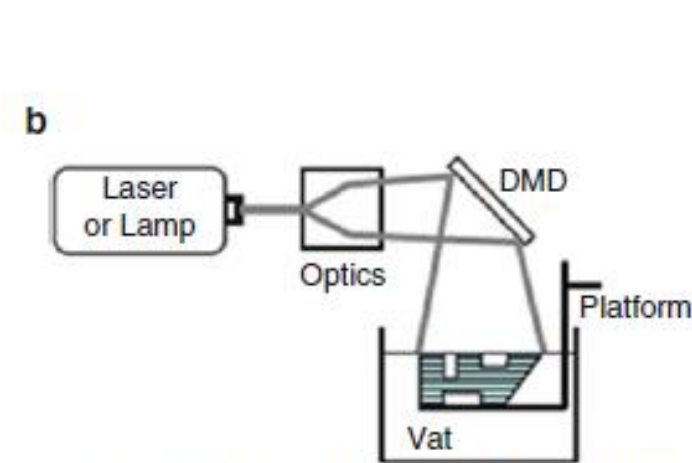
- The first concept of interest here is irradiance, the radiant power of the laser per unit area, $H(x, y, z)$. As the laser scans a line, the radiant power is distributed over a finite area (beam spots are not infinitesimal).
- The irradiance at any point x, y, z in the resin is related to the irradiance at the surface, assuming that the resin absorbs radiation according to the Beer–Lambert Law.

The configurations SL Process:

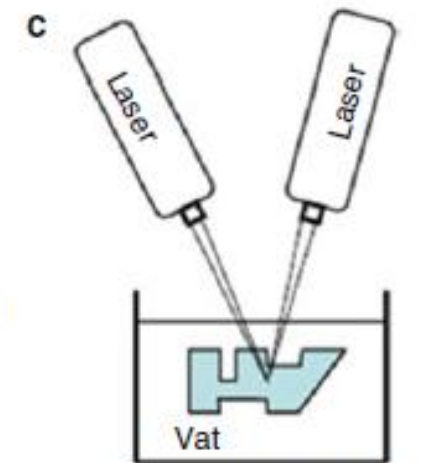
- Vector scan, or point-wise, approaches typical of commercial SL machines
- Mask projection, or layer-wise, approaches, that irradiate entire layers at one time, and
- Two-photon approaches that are essentially high-resolution point-by-point approaches



schematic of vector scan SL



Schematic of mask projection approach to SL.



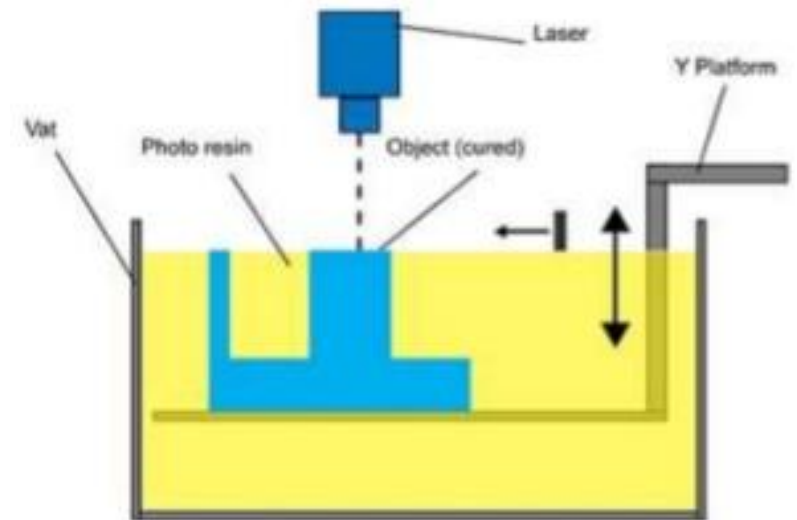
Two-photon approach

Vat Photo-Polymerization

- Vat polymerisation uses a vat of liquid photopolymer resin, out of which the model is constructed layer by layer. An ultraviolet (UV) light is used to cure or harden the resin where required, whilst a platform moves the object being made downwards after each new layer is cured.
- As the process uses liquid to form objects, there is no structural support from the material during the build phase., unlike powder based methods, where support is given from the unbound material. In this case, support structures will often need to be added. Resins are cured using a process of photo polymerisation (Gibson et al., 2010) or UV light, where the light is directed across the surface of the resin with the use of motor controlled mirrors (Grenda, 2009). Where the resin comes in contact with the light, it cures or hardens.

Photopolymerisation – Step by Step

- The build platform is lowered from the top of the resin vat downwards by the layer thickness.
- A UV light cures the resin layer by layer. The platform continues to move downwards and additional layers are built on top of the previous.
- Some machines use a blade which moves between layers in order to provide a smooth resin base to build the next layer on.
- After completion, the vat is drained of resin and the object removed.



Vector Scan Micro-Vat Photopolymerization

Several processes were developed exclusively for microfabrication applications based on photopolymerization principles using both lasers and X-rays as the energy source. These processes build complex shaped parts that are typically less than 1 mm in size. They are referred to as

- **Microstereolithography (MSL),**
- **Integrated Hardened Stereolithography (IH),**
- **Deep X-ray Lithography (DXRL)**

The following specifications of a typical point-wise microstereolithography process

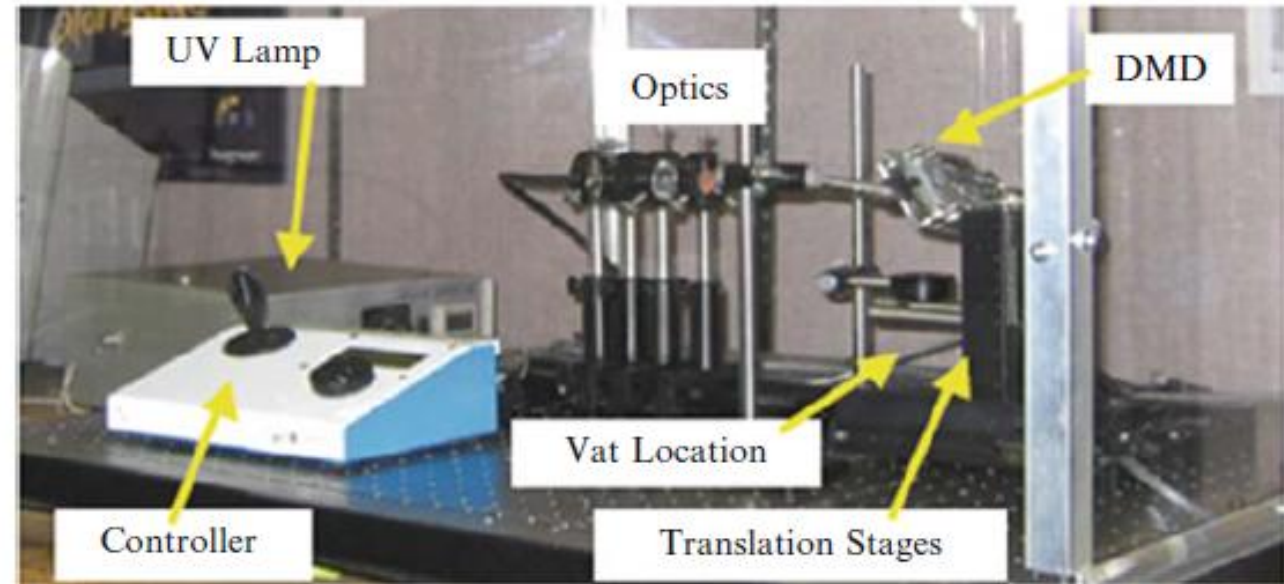
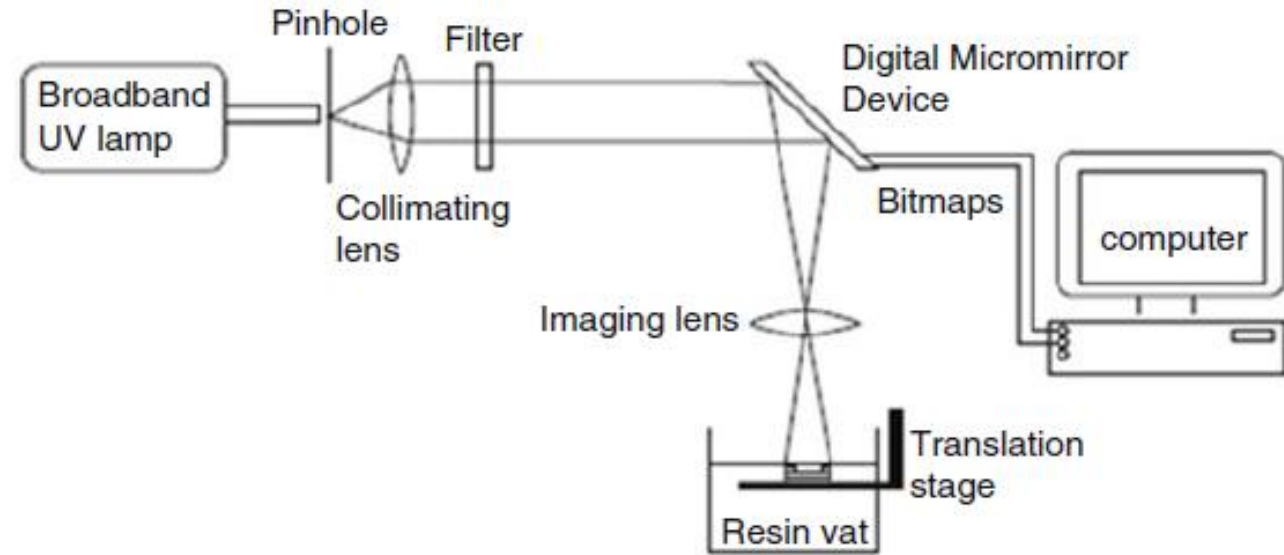
- 5- μm spot size of the UV beam
- Positional accuracy is 0.25 μm (in the x–y directions) and 1.0 μm in the z direction
- Minimum size of the unit of hardened polymer is 5 μm 5 μm 3 μm (in x, y, z)
- Maximum size of fabrication structure is 10 mm 10 mm 10 mm

The capability of building around inserted components has also been proposed for components such as ultrafiltration membranes and electrical conductors. Applications include fluid chips for protein synthesis and bioanalysis.

The bioanalysis system was constructed with integrated valves and pumps that include a stacked modular design, 13x13 mm² and 3 mm thick, each of which has a different fluid function. However, the full extent of integrated processing on silicon has not yet been demonstrated. The benefits of greater design flexibility and lower cost of fabrication may be realized in the future.

Microscale VP has been commercialized by MicroTEC GmbH, Germany. Although machines are not for sale, the company offers customer-specific services.

The company has developed machines based on **point-wise** as well as **layer-wise** photopolymerization principles. Their Rapid Micro Product Development (RMPD) machines using a He–Cd laser enable construction of small parts layer-by-layer (as thin as $1\ \mu\text{m}$) with a high surface quality in the subnanometer range and with a feature definition of $<10\ \mu\text{m}$.



Process Benefits and Drawbacks

Two of the main advantages of vat photopolymerization technology over other AM technologies are part **accuracy and surface finish**. These characteristics led to the widespread usage of **vector scan stereolithography** parts as form, fit, and, to a lesser extent, functional prototypes as the rapid prototyping field developed. Typical dimensional accuracies for SL machines are often quoted as a ratio of an error per unit length. For example, accuracy of an SLA-250 is typically quoted as **50 μm** . Modern SL machines are somewhat more accurate. Surface finish of SL parts ranges from submicron Ra for upfacing surfaces to over **100 μm Ra** for surfaces at slanted angles.

Another advantage of VP technologies is their **flexibility, supporting** many different machine configurations and size scales. **Different light sources can be used, including lasers, lamps, or LEDs**, as well as **different pattern generators**, such as scanning galvanometers or DMDs. The size range that has been demonstrated with VP technologies is vast: from the 1.5 m vat in the iPro 9000XL SLA Center to the 100 nm features possible with 2-photon photopolymerization.



Process Benefits and Drawbacks

A drawback of VP processes is their usage of photopolymers, since the chemistries are **limited to acrylates and epoxies** for commercial materials. Although quite a few other material systems are photopolymerizable, **none have emerged as commercial successes to displace the current chemistries.**

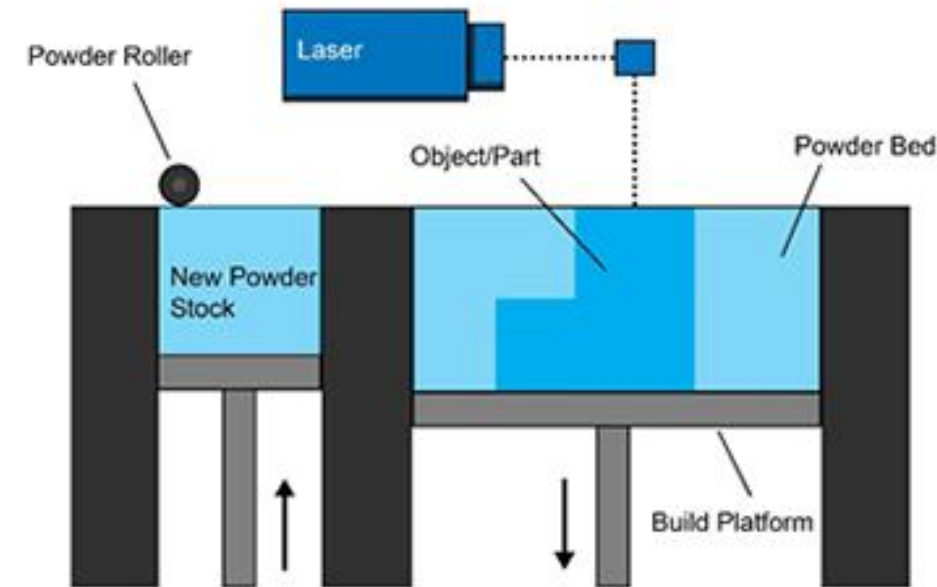
Generally, the current SL materials **do not have the impact strength and durability** of good quality **injection molded thermoplastics**. Additionally, they are known to age, resulting in **degraded mechanical properties over time**. These limitations prevent SL processes from being used for many production applications.

Powder Bed Fusion

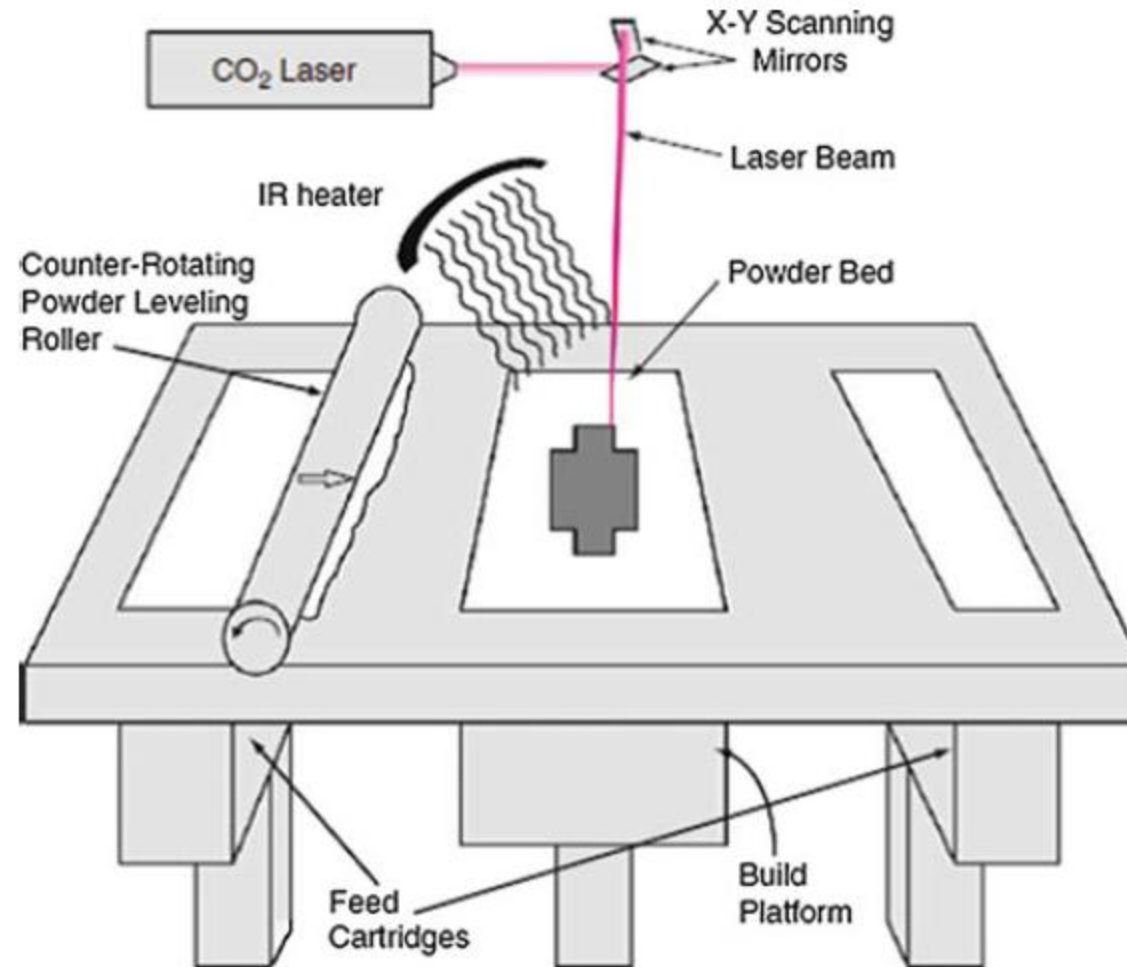
- The Powder Bed Fusion process includes the following commonly used printing techniques: Direct metal laser sintering (DMLS), Electron beam melting (EBM), Selective heat sintering (SHS), Selective laser melting (SLM) and Selective laser sintering (SLS).
- Powder bed fusion (PBF) methods use either a laser or electron beam to melt and fuse material powder together. Electron beam melting (EBM), methods require a vacuum but can be used with metals and alloys in the creation of functional parts. All PBF processes involve the spreading of the powder material over previous layers. There are different mechanisms to enable this, including a roller or a blade. A hopper or a reservoir below of aside the bed provides fresh material supply. Direct metal laser sintering (DMLS) is the same as SLS, but with the use of metals and not plastics. The process sinters the powder, layer by layer. Selective Heat Sintering differs from other processes by way of using a heated thermal print head to fuse powder material together. As before, layers are added with a roller in between fusion of layers. A platform lowers the model accordingly.

Powder Bed Fusion – Step by Step

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



Selective Laser Sintering Process



Materials

In principle, all materials that can be melted and resolidified can be used in PBF processes.

Thermoplastic materials are well-suited for powder bed processing because of their relatively low melting temperatures, low thermal conductivities, and low tendency for balling. Polymers in general can be classified as either a thermoplastic or a thermoset polymer. Thermoset polymers are typically not processed using PBF into parts, since PBF typically operates by melting particles to fabricate part cross sections, but thermosets degrade, but do not melt, as their temperature is increased. Thermoplastics can be classified further in terms of their crystallinity. Amorphous polymers have a random molecular structure, with polymer chains randomly intertwined. In contrast, crystalline polymers have a regular molecular structure, but this is uncommon. Much more common are semi-crystalline polymers which have regions of regular structure, called crystallites. Amorphous polymers melt over a fairly wide range of temperatures. As the crystallinity of a polymer increases, however, its melting characteristics tend to become more centered around a well defined melting point.

At present, the most common material used in PBF is polyamide, a thermoplastic polymer, commonly known in the US as nylon.

Materials

Polystyrene-based materials with low residual ash content are particularly suitable for making sacrificial patterns for investment casting using polymer Laser sintering (pLS). Interestingly, polystyrene is an amorphous polymer, but is a successful example material due to its intended application. Porosity in an investment casting pattern aids in melting out the pattern after the ceramic shell is created.

Elastomeric thermoplastic polymers are available for producing highly flexible parts with rubber-like characteristics. These elastomers have good resistance to degradation at elevated temperatures and are resistant to chemicals like gasoline and automotive coolants. Elastomeric materials can be used to produce gaskets, industrial seals, shoe soles, and other components.

Researchers have investigated quite a few polymers for biomedical applications. Several types of biocompatible and biodegradable polymers have been processed using pLS, including polycaprolactone (PCL), polylactide (PLA), and poly-Llactide (PLLA). Composite materials consisting of PCL and ceramic particles, including hydroxyapatite and calcium silicate, have also been investigated for the fabrication of bone replacement tissue scaffolds.

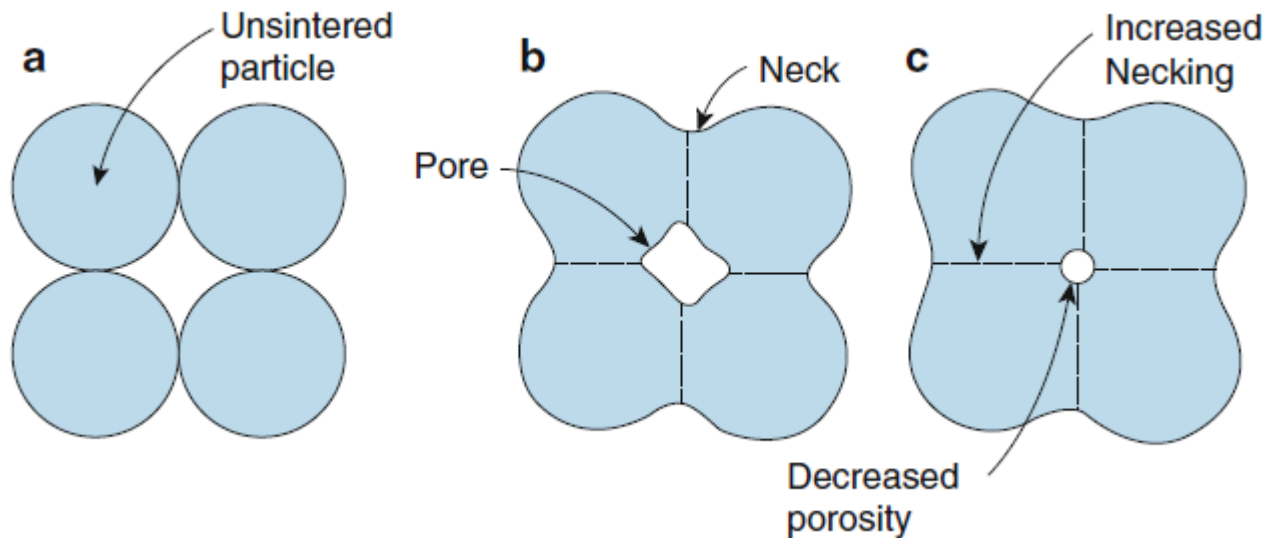
Materials

A wide range of metals has been processed using PBF. Generally, any metal that can be welded is considered to be a good candidate for PBF processing. Several types of steels, typically stainless and tool steels, titanium and its alloys, nickel-base alloys, some aluminum alloys, and cobalt-chrome have been processed and are commercially available in some form. Additionally, some companies now offer PBF of precious metals, such as silver and gold.

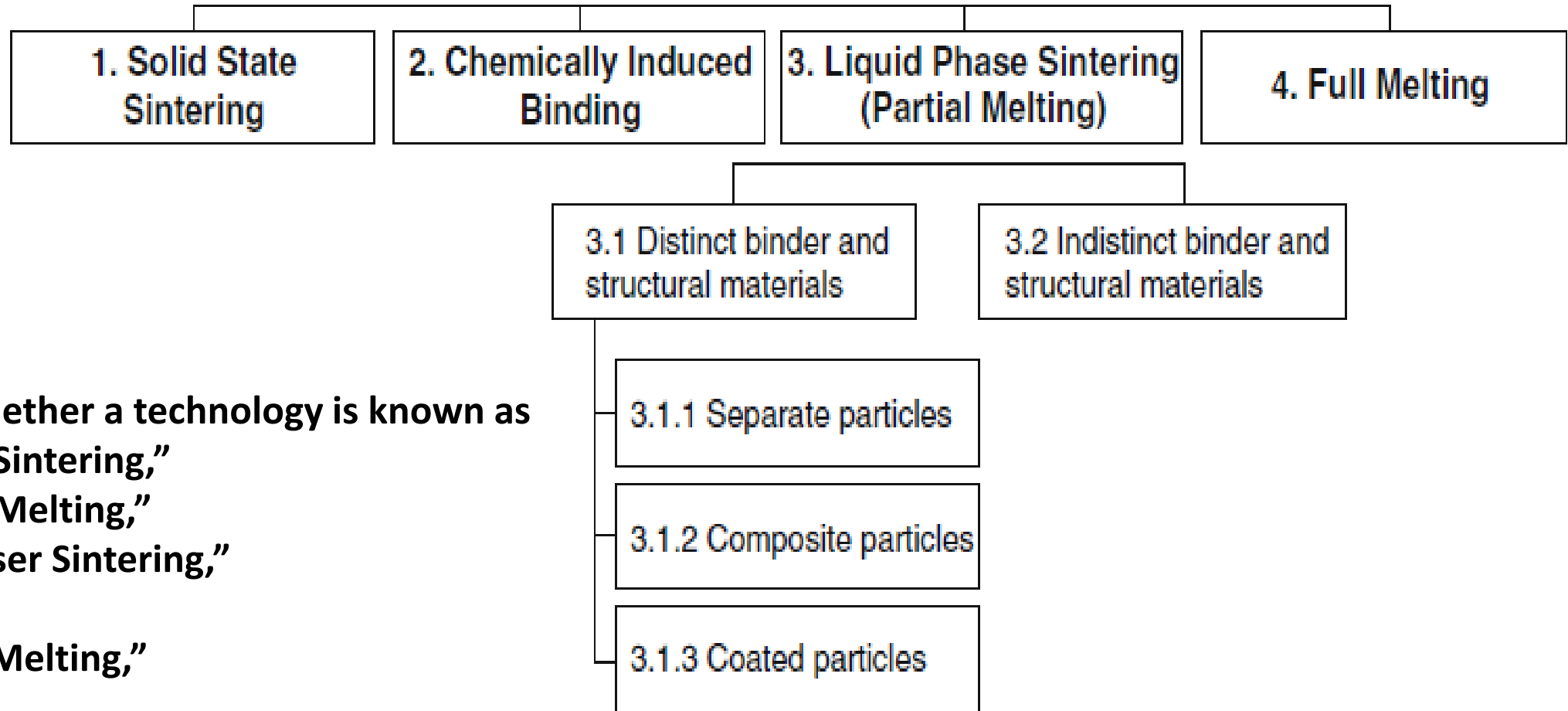
Ceramic materials are generally described as compounds that consist of metaloxides, carbides, and nitrides and their combinations. Several ceramic materials are available commercially including aluminum oxide and titanium oxide. Commercial machines were developed by a company called Phenix Systems in France, which was acquired by 3D Systems in 2013. 3D Systems also says it offers cermets, which are metal-ceramic composites.

Solid-state sintering.

- (a) Closely packed particles prior to sintering.
- (b) Particles agglomerate at temperatures above one half of the absolute melting temperature, as they seek to minimize free energy by decreasing surface area.
- (c) As sintering progresses, neck size increases and pore size decreases

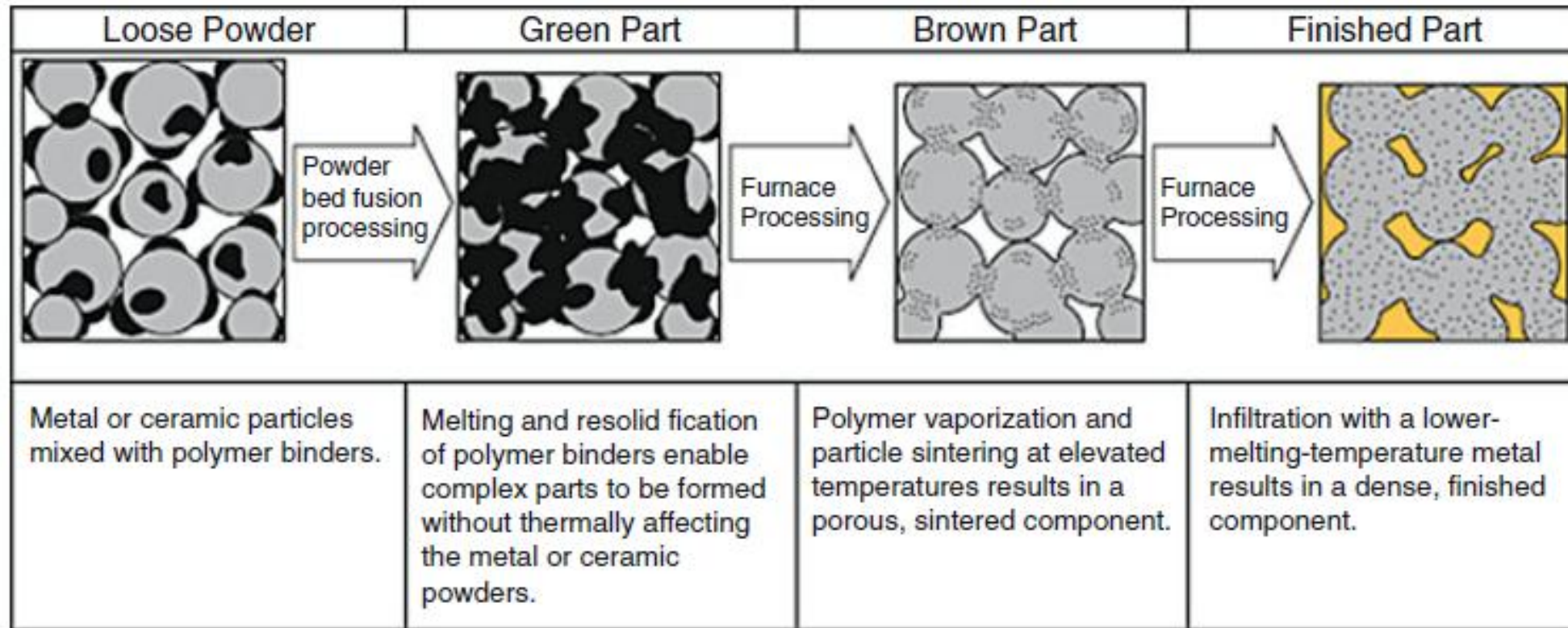


Primary Binding Mechanisms in Powder Bed Fusion Processes



Regardless of whether a technology is known as
“Selective Laser Sintering,”
“Selective Laser Melting,”
“Direct Metal Laser Sintering,”
“Laser Cusing,”
“Electron Beam Melting,”

Indirect processing of metal and ceramic powders using PBF



PBF Process Parameters and Modeling

Use of optimum process parameters is extremely important for producing satisfactory parts using PBF processes.

“laser” processing and parameters, thermal energy sources, such as electron beams or infrared heaters.

In PBF, process parameters can be lumped into four categories:

- (1) Laser-related parameters (laser power, spot size, pulse duration, pulse frequency, etc.),
- (2) Scan related parameters (scan speed, scan spacing, and scan pattern),
- (3) powder-related parameters (particle shape, size, and distribution, powder bed density, layer thickness, material properties, etc.), and
- (4) Temperature-related parameters (powder bed temperature, powder feeder temperature, temperature uniformity, etc.).

It should be noted that most of these parameters are strongly interdependent and are mutually interacting. The required laser power, for instance, typically increases with melting point of the material and lower powder bed temperature, and also varies depending upon the absorptivity characteristics of the powder bed, which is influenced by material type and powder shape, size, and packing density.

PBF Process Parameters and Modeling

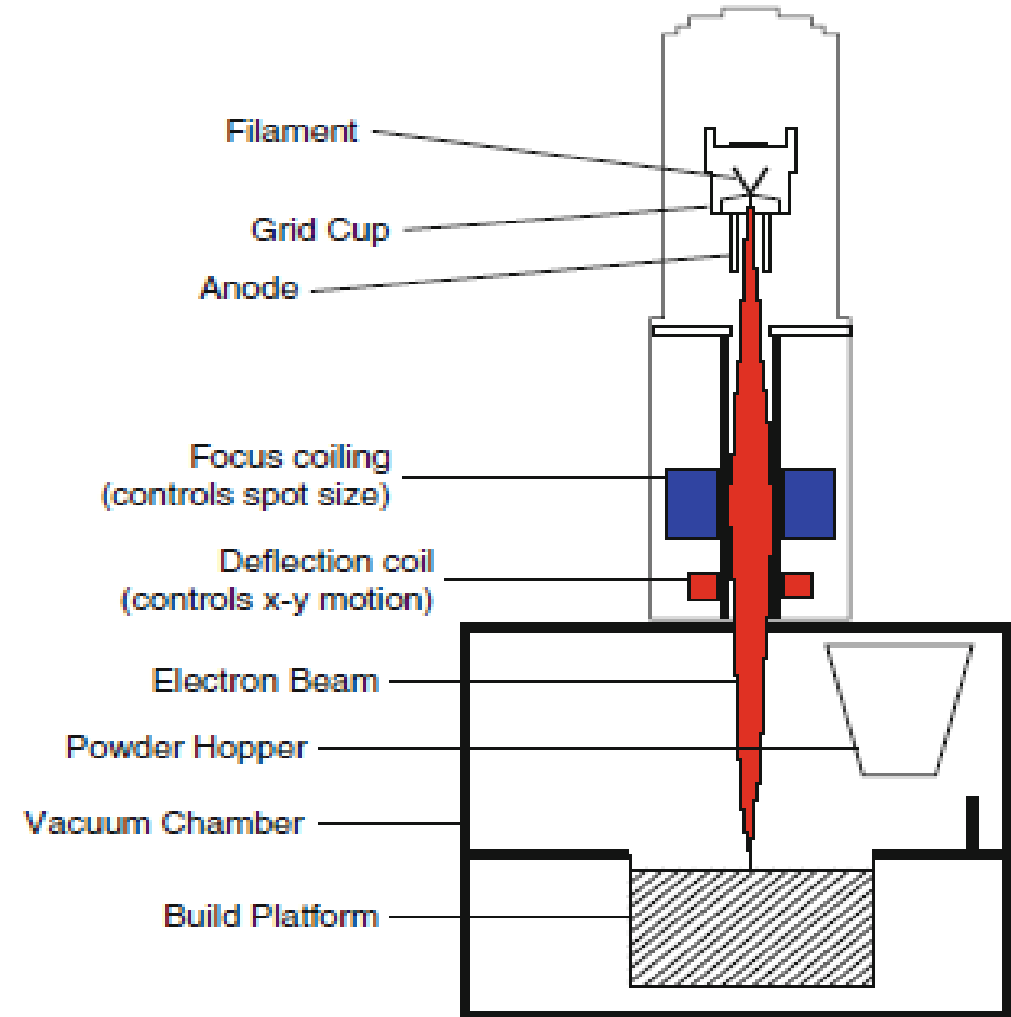
- Powder shape, size, and distribution strongly influence laser absorption characteristics as well as powder bed density, powder bed thermal conductivity, and powder spreading.
- Finer particles provide greater surface area and absorb laser energy more efficiently than coarser particles.
- Powder bed temperature, laser power, scan speed, and scan spacing must be balanced to provide the best tradeoff between melt pool size, dimensional accuracy, surface finish, build rate, and mechanical properties.
- The powder bed temperature should be kept uniform and constant to achieve repeatable results. Generally, high-laser-power/high-bed-temperature combinations produce dense parts, but can result in part growth, poor recyclability, and difficulty cleaning parts.
- On the other hand, low-laser-power/lowbed-temperature combinations produce better dimensional accuracy, but result in lower density parts and a higher tendency for layer delamination.
- High-laser-power combined with low-part-bed-temperatures result in an increased tendency for nonuniform shrinkage and the build-up of residual stresses, leading to curling of parts.

PBF Process Parameters and Modeling

- Laser power, spot size and scan speed, and bed temperature together determine the energy input needed to fuse the powder into a useable part.
- The longer the laser dwells in a particular location, the deeper the fusion depth and the larger the melt pool diameter. Typical layer thicknesses range from 0.02 to 0.15 mm.
- Operating at lower laser powers requires the use of lower scan speeds in order to ensure proper particle fusion.
- Melt pool size is highly dependent upon settings of laser power, scan speed, spot size, and bed temperature. Scan spacing should be selected to ensure a sufficient degree of melt pool overlap between adjacent lines of fused material to ensure robust mechanical properties.
- The powder bed density, as governed by powder shape, size, distribution, and spreading mechanism, can strongly influence the part quality.
- Powder bed densities typically range between 50 and 60 % for most commercially available powders, but may be as low as 30 % for irregular ceramic powders.
- Generally the higher the powder packing density, the higher the bed thermal conductivity and the better the part mechanical properties.

ELECTRON BEAM MELTING (EBM)

- Electron Beam Melting (EBM) has become a successful approach to PBF. In contrast to laser-based systems, EBM uses a high-energy electron beam to induce fusion between metal powder particles. This process was developed at Chalmers University of Technology, Sweden, and was commercialized by Arcam AB, Sweden in 2001.
- Similarly to SLM; in the EBM process, a focused electron beam scans across a thin layer of pre-laid powder, causing localized melting and resolidification as per the slice cross-section.
- However, there are a number of differences between how SLM and EBM are typically practiced.



ELECTRON BEAM MELTING (EBM)

Electron beams are inherently different from laser beams, as electron beams are made up of a stream of electrons moving near the speed of light, whereas, laser beams are made up of photons moving at the speed of light. When an electron beam is passed through a gas at atmospheric pressure, for instance, the electrons interact with the atoms in the gas and are deflected. In contrast, a laser beam can pass through a gas unaffected as long as the gas is transparent at the laser wavelength.

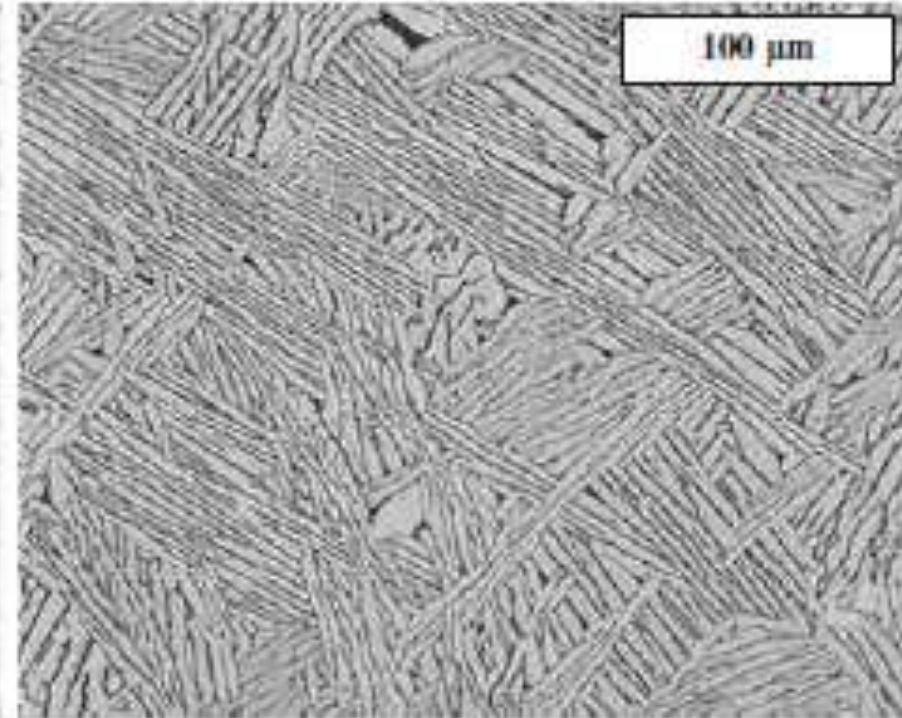
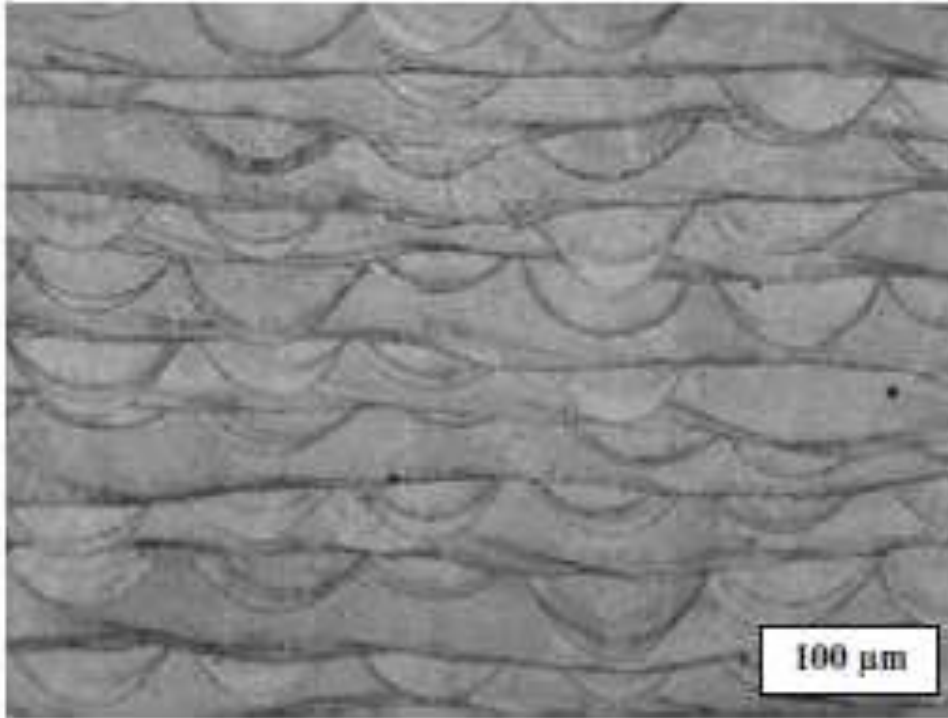
Thus, EBM is practiced in a low-partial-pressure vacuum environment (a small amount of inert gas is swept through to remove gaseous byproducts and oxygen), whereas SLM is practiced in an inert gas atmosphere at atmospheric pressure. Electrons have a negative charge and are focused and deflected magnetically, whereas photons are optically focused and deflected using mirrors attached to motors. As a result, since magnetic coils have an almost instantaneous response to changing input conditions, an electron beam can be scanned slowly or very rapidly. In essence an electron beam can be moved instantaneously from one location to another without needing to traverse the area in-between.

Electron beam generation is typically a much more efficient process than laser beam generation. When a voltage difference is applied to the heated filament in an electron beam system, most of the electrical energy is converted into the electron beam, and higher beam energies (above 1 kW) are available at a moderate cost.

ELECTRON BEAM MELTING (EBM)

- The conductivity of the powder bed in EBM must be high enough that powder particles do not become highly negatively charged, and scan strategies must be used to avoid build-up of regions of negatively charged particles. In practice, electron beam energy is more diffuse; in part, so as not to build up too great a negative charge in any one location. As a result, the effective melt pool size increases, creating a larger heat-affected zone.
- Consequently, the minimum feature size, resolution and surface finish of an EBM process is typically larger than an SLM process. As mentioned above, in EBM the powder bed must be conductive. Thus, EBM can only be used to process conductive materials (e.g., metals) whereas, lasers can be used with any material that absorbs energy at the laser wavelength (e.g., metals, polymers and ceramics).
- Electron beam generation is typically a much more efficient process than laser beam generation. When a voltage difference is applied to the heated filament in an electron beam system, most of the electrical energy is converted into the electron beam, and higher beam energies (above 1 kW) are available at a moderate cost. By contrast, it is common for only 10–20% of the total electrical energy input for laser systems to be converted into beam energy, with the remaining energy lost in the form of heat. In addition, lasers with beam energies above 1 kW are typically much more expensive than comparable electron beams with similar energies. Thus, electron beams are a less costly high energy source than laser beams. Newer fiber lasers, however, are more simple in their design, more reliable to maintain, and more efficient to use (with conversion efficiencies reported of 70–80% for some fiber lasers) and thus, this energy cost advantage for electron beams may not be a major advantage in the future.

Representative CoCrMo SLM microstructure (*left*, courtesy EOS), and
Ti6Al4V EBM microstructure (*right*, courtesy Arcam)



Differences between EBM and SLM

Characteristic	Electron beam melting	Selective laser melting
Thermal source	Electron beam	Laser
Atmosphere	Vacuum	Inert gas
Scanning	Deflection coils	Galvanometers
Energy absorption	Conductivity-limited	Absorptivity-limited
Powder pre-heating	Use electron beam	Use infrared heaters
Scan speeds	Very fast, magnetically-driven	Limited by galvanometer inertia
Energy costs	Moderate	High
Surface finish	Moderate to poor	Excellent to moderate
Feature resolution	Moderate	Excellent
Materials	Metals (conductors)	Polymers, metals and ceramics

Process Benefits and Drawbacks

- PBF can process a very wide variety of materials, in contrast to many other AM processes.
- It is easier to control the processing of semicrystalline polymers, the PBF processing of amorphous polymers has been successful. Many metals can be processed; as mentioned, if a metal can be welded, it is a good candidate for metal Laser Sintering (mLS).
- Some ceramic materials are commercially available, but quite a few others have been demonstrated in research. During part building, loose powder is a sufficient support material for polymer PBF. This saves significant time during part building and post-processing, and enables advanced geometries that are difficult to post-process when supports are necessary.
- As a result, internal cooling channels and other complex features that would be impossible to machine are possible in polymer PBF.
- Supports, however, are required for most metal PBF processes. The high residual stresses experienced when processing metals means that support structures are typically required to keep the part from excessive warping.
- This means that postprocessing of metal parts after AM can be expensive and time consuming. Small features (including internal cooling channels) can usually be formed without supports; but the part itself is usually constrained to a substrate at the bottom of the build platform to keep it from warping.
- As a result, the orientation of the part and the location of supports are key factors when setting up a build. Accuracy and surface finish of powder-based AM processes are typically inferior to liquid-based processes.

Process Benefits and Drawbacks

- However, accuracy and surface finish are strongly influenced by the operating conditions and the powder particle size.
- Finer particle sizes produce smoother, more accurate parts but are difficult to spread and handle. Larger particle sizes facilitate easier powder processing and delivery, but hurt surface finish, minimum feature size and minimum layer thickness.
- The build materials used in these processes typically exhibit 3–4 % shrinkage, which can lead to part distortion. Materials with low thermal conductivity result in better accuracy as melt pool and solidification are more controllable and part growth is minimized when heat conduction is minimized.
- With PBF processes, total part construction time can take longer than other additive manufacturing processes because of the preheat and cool-down cycles involved.
- However, as is the case with several newer machine designs, removable build platforms enable preheat and cool-down to occur off-line, thus enabling much greater machine productivity.
- Additionally, the ability to nest polymer parts in three-dimensions, as no support structures are needed, mean that many parts can be produced in a single build, thus dramatically improving the productivity of these processes when compared with processes that require supports.

APPLICATIONS OF POWDER BED FUSION PROCESSES

1. Automotive applications of powder bed fusion

The applications of powder bed fusion in the automotive industry are many, from prototyping to light weighting of components. Listed below are some examples of where the technology is used in the automotive industry:

- **Tyre molds** – Tyre tread molds often contain very thin but complex features. They improve the tyres' functionality and give them a more stable tread profile throughout their lifespan. Powder bed fusion outfits Michelin tyre molds with extremely thin structures and other advanced geometry that would be impossible or extremely expensive to manufacture with standard techniques.
- **Seat belt bracket** – General motors have turned to powder bed fusion to reduce the weight and assembly complexity of their seat belt brackets. Using generative design, a single component was created that had the required structural strength and took the place of the eight sub-components of previous designs.
- **Brake caliper** – Bugatti 3D printed a titanium brake caliper that is normally made out of aluminium. The resulting caliper was stronger than the original and weighed 40% less.

APPLICATIONS OF POWDER BED FUSION PROCESSES

2. Medical applications of powder bed fusion

The medical industry is a major adopter of 3D printing technology – especially powder bed fusion. This is in part due to the wide range of biocompatible materials that are well-suited to these printers as well as the fact that the process can produce a variety of complex geometries. Listed below are some applications of powder bed fusion for medical technology:

- **Jaw reconstruction** – An entire jaw bone was printed out of titanium and implanted into a patient. A custom jaw bone was designed based on x-rays of the patient's skull. This artificial jaw bone had cavities built into it to allow for muscle attachment and nerve growth.
- **Knee replacement** – The cartilage in knee joints wears down with time and in some cases the condition can no longer be managed with medication. In this case a metal knee joint may be implanted to reinforce the area. A custom knee joint is created from biocompatible material for each patient by making use of CT-scan data.
- **Hip joint** – 3D-printed hip joints were first implanted over a decade ago and have now become common. Tens of thousands of hip joints have been implanted into patients that make use of biocompatible titanium and complex porous structures to promote bone stitching into the joint. This technology has benefited a wide range of patients and offers a drastic improvement over older implants.

APPLICATIONS OF POWDER BED FUSION PROCESSES

3. Aerospace applications of powder bed fusion

The aerospace industry, one of the early adopters of powder bed fusion for metal parts, operates at the very edge of material science and engineering technology in order to push the limits of what's possible. Listed below are some applications of powder bed fusion in aerospace engineering:

- **Rocket engine combustion chamber** – Launcher, an American rocket startup, used powder bed fusion to consolidate the various parts of a rocket engine combustion chamber into one component, drastically reducing part complexity. Furthermore, it allows for the inclusion of internal cooling channels within the structure of the rocket to further improve the engine's performance. This component experiences extreme temperatures and pressures and serves as a testament to the performance of 3Dprinted parts.

GE9C Engine – The engines on the Boeing 777x are the largest and most powerful commercial jet engines to date and incorporate over 300 3D-printed parts. They are 10% more fuel efficient when compared to their predecessors. This drastic increase proves that the applications of powder bed fusion are set to grow considerably within the aerospace industry.

- **Injector head** – The Ariane 6 rocket booster made use of powder bed fusion for the manufacture of a complex rocket engine part known as an injector head. This allowed for a simplification in the assembly from 248 parts to only one. It significantly reduced the production time from three months to a day and a half as well as halving the cost of the part.

Extrusion-Based Systems

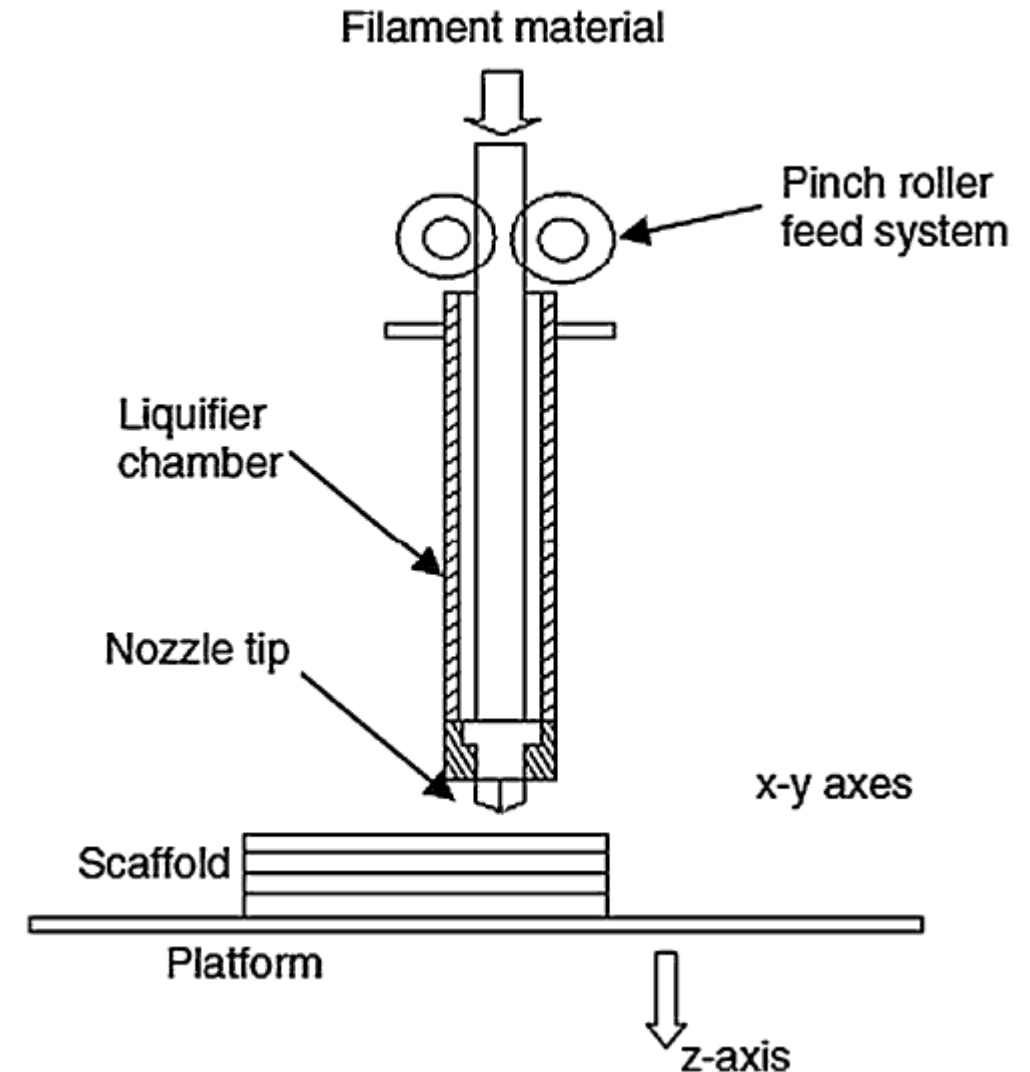
Extrusion-based technology is currently the most popular on the market. Whilst there are other techniques for creating the extrusion, heat is normally used to melt bulk material in a small, portable chamber. The material is pushed through by a tractor-feed system, which creates the pressure to extrude.

- A mathematical or physics-based understanding of extrusion processes can quickly become complex, since it can involve many nonlinear terms.
- The basic science involves extrusion of highly viscous materials through a nozzle. It is reasonable to assume that the material flows as a Newtonian fluid in most cases .
- Most of the discussion in these sections will assume the extrusion is of molten material and may therefore include temperature terms.
- For solidification, these temperature terms are generally expressed relative to time; and so temperature could be replaced by other time-dependent factors to describe curing or drying processes.

Basic Principles

There are a number of key features that are common to any extrusion-based system:

- Loading of material
- Liquification of the material
- Application of pressure to move the material through the nozzle
- Extrusion
- Plotting according to a predefined path and in a controlled manner
- Bonding of the material to itself or secondary build materials to form a coherent solid structure
- Inclusion of support structures to enable complex geometrical features

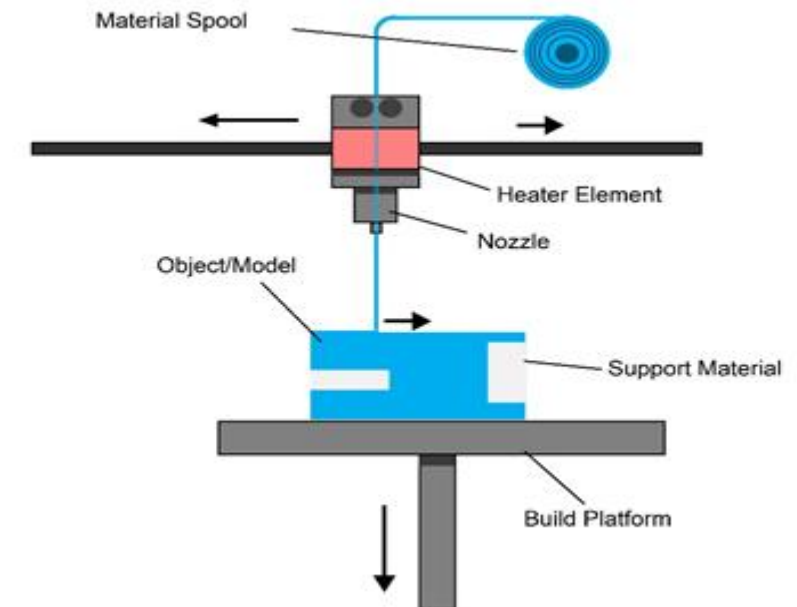


Material Extrusion

- Fuse deposition modelling (FDM) is a common material extrusion process and is trademarked by the company Stratasys. Material is drawn through a nozzle, where it is heated and is then deposited layer by layer. The nozzle can move horizontally and a platform moves up and down vertically after each new layer is deposited. It is a commonly used technique used on many inexpensive, domestic and hobby 3D printers.
- The process has many factors that influence the final model quality but has great potential and viability when these factors are controlled successfully. Whilst FDM is similar to all other 3D printing processes, as it builds layer by layer, it varies in the fact that material is added through a nozzle under constant pressure and in a continuous stream. This pressure must be kept steady and at a constant speed to enable accurate results (Gibson et al., 2010). Material layers can be bonded by temperature control or through the use of chemical agents. Material is often added to the machine in spool form as shown in the diagram.

Material Extrusion – Step by Step

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



MATERIALS

The most popular material is the ABSplus material, which can be used on all current Stratasys FDM machines. This is an updated version of the original ABS (acrylonitrile butadiene styrene) material that was developed for earlier FDM technology. Users interested in a translucent effect may opt for the ABSi material, which has similar properties to other materials in the ABS range. Some machines also have an option for ABS blended with Polycarbonate. Table 6.1 shows properties for various ABS materials and blends.

Variations in properties for the ABS range of FDM materials

Property	ABS	ABSi	ABSplus	ABS/PC
Tensile strength	22 MPa	37 MPa	36 MPa	34.8 MPa
Tensile modulus	1,627 MPa	1,915 MPa	2,265 MPa	1,827 MPa
Elongation	6%	3.1%	4%	4.3%
Flexural strength	41 MPa	61 MPa	52 MPa	50 MPa
Flexural modulus	1,834 MPa	1,820 MPa	2,198 MPa	1,863 MPa
IZOD impact	106.78 J/m ²	101.4 J/m ²	96 J/m ²	123 J/m ²
Heat deflection @ 66 psi	90°C	87°C	96°C	110°C
Heat deflection @ 264 psi	76°C	73°C	82°C	96°C
Thermal expansion	5.60E-05 in/in/F	6.7E-6 in/in/F	4.90E-05 in/in/F	4.10E-5 in/in F
Specific gravity	1.05	1.08	1.04	1.2

PLOTTING AND PATH CONTROL

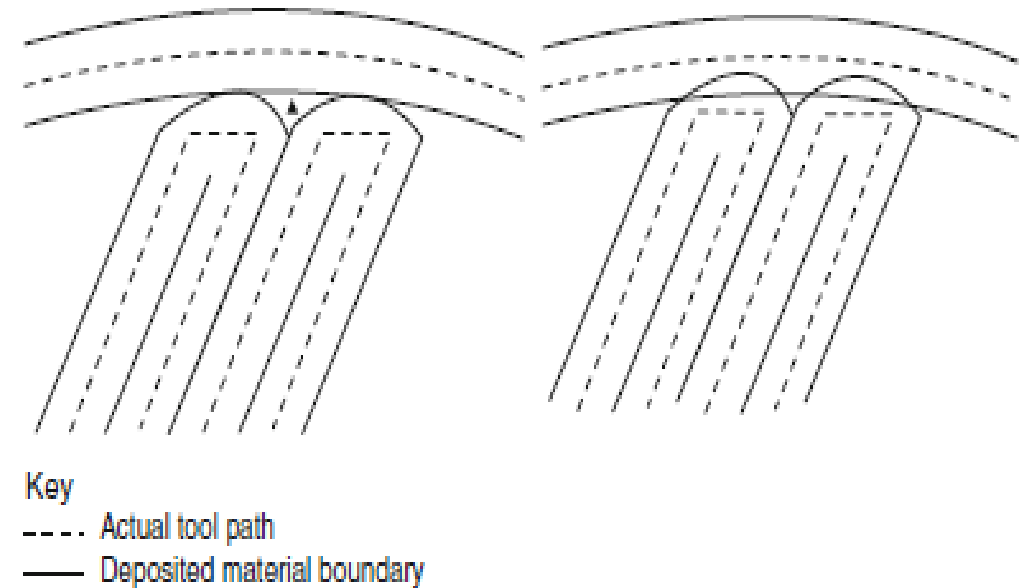
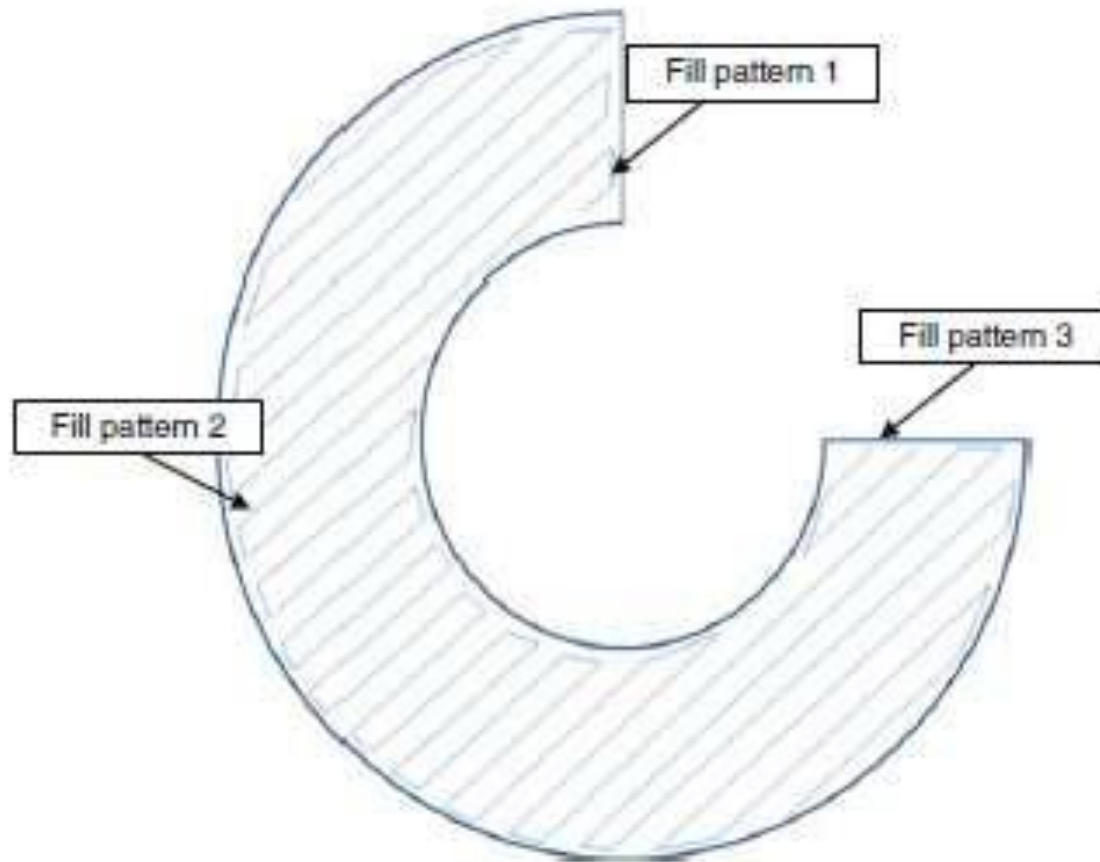
Nearly all additive manufacturing systems, extrusion-based machines mostly take input from CAD systems using the generic STL file format. This file format enables easy extraction of the slice profile, giving the outline of each slice.

As with most systems, the control software must also determine how to fill the material within the outline. This is particularly crucial to this type of system, however, since extrusion heads physically deposit material that fills previously vacant space.

There must be clear access for the extrusion head to deposit fill material within the outline without compromising the material that has already been laid down.

Additionally, if the material is not laid down close enough to adjacent material, it will not bond effectively. In contrast, laser-based systems can permit, and in fact generally require, a significant amount of overlap from one scan to the next and thus there are no head collision or overfilling-equivalent phenomena.

A typical fill pattern using an extrusion-based system, created in three stages



It can be seen that precise control of extrusion is a complex trade-off, dependent on a significant number of parameters, including:

Input pressure: This variable is changed regularly during a build, as it is tightly coupled with other input control parameters. Changing the input pressure (or force applied to the material) results in a corresponding output flow rate change. A number of other parameters, however, also affect the flow to a lesser degree.

- **Temperature:** Maintaining a constant temperature within the melt inside the chamber would be the ideal situation. However, small fluctuations are inevitable and will cause changes in the flow characteristics. Temperature sensing should be carried out somewhere within the chamber and therefore a loosely coupled parameter can be included in the control model for the input feed pressure to compensate for thermal variations. As the heat builds up, the pressure should drop slightly to maintain the same flow rate.

- **Nozzle diameter:** This is constant for a particular build, but many extrusion based systems do allow for interchangeable nozzles that can be used to offset speed against precision.

- **Material characteristics:** Ideally, control models should include information regarding the materials used. This would include viscosity information that would help in understanding the material flow through the nozzle. Since viscous flow, creep, etc. are very difficult to predict, accurately starting and stopping flow can be difficult.
- **Gravity and other factors:** If no pressure is applied to the chamber, it is possible that material will still flow due to the mass of the molten material within the chamber causing a pressure head. This may also be exacerbated by gaseous pressure buildup inside the chamber if it is sealed. Surface tension of the melt and drag forces at the internal surfaces of the nozzle may retard this effect.
- **Temperature build up within the part:** All parts will start to cool down as soon as the material has been extruded. However, different geometries will cool at different rates. Large, massive structures will hold their heat for longer times than smaller, thinner parts, due to the variation in surface to volume ratio. Since this may have an effect on the surrounding environment, it may also affect machine control.

Taking these and other factors into consideration can help one better control the flow of material from the nozzle and the corresponding precision of the final part. However, other uncontrollable or marginally controllable factors may still prove problematic to precisely control flow. Many extrusion-based systems, for instance, resort to periodically cleaning the nozzles from time to time to prevent build-up of excess material adhered to the nozzle tip.

Bio-extrusion

- Extrusion-based technology has a large variety of materials that can be processed.
- If a material can be presented in a liquid form that can quickly solidify, then it is suitable to this process. As mentioned earlier, the creation of this liquid can be either through thermal processing of the material to create a melt, or by using some form of chemical process where the material is in a gel form that can dry out or chemically harden quickly.
- These techniques are useful for bioextrusion. Bioextrusion is the process of creating biocompatible and/or biodegradable components that are used to generate frameworks, commonly referred to as “scaffolds,” that play host to animal cells for the formation of tissue (tissue engineering).
- Such scaffolds should be porous, with micropores that allow cell adhesion and macropores that provide space for cells to grow.

Based on the biocompatible **polymer, polycaprolactone (PCL)**.

Most tissue engineering is still, however, in research form; investigating many aspects of the process, including material choice, structural strength of scaffolds, coatings, biocompatibility, and effectiveness within various clinical scenarios.

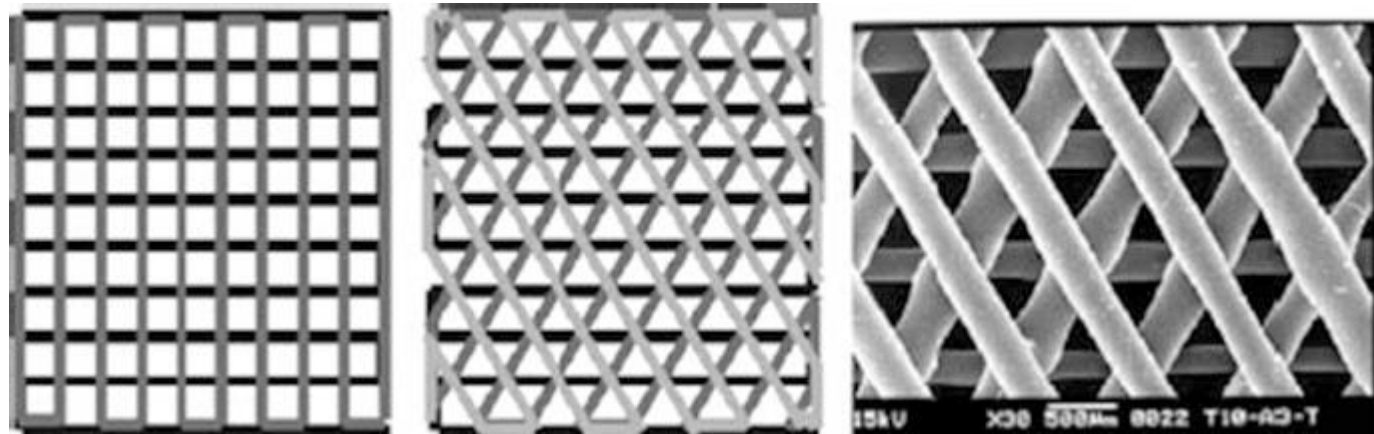
Many systems are in fact developed in-house to match the specific interests of the researchers. There are however a small number of systems that are also available commercially to research labs.

Gel Formation

One common method of creating scaffolds is to use hydrogels. These are polymers that are water insoluble but can be dispersed in water. Hydrogels can therefore be extruded in a jelly-like form. Following extrusion, the water can be removed and a solid, porous media remains. Such a media can be very biocompatible and conducive to cell growth with low toxicity levels. Hydrogels can be based on naturally occurring polymers or synthetic polymers. The natural polymers are perhaps more biocompatible whereas the synthetic ones are stronger. Synthetic hydrogels are rarely used in tissue engineering, however, because of the use of toxic reagents. Overall, use of hydrogels results in weak scaffolds that may be useful for soft tissue growth.

Scaffold Architectures

Different scaffold designs showing a porous structure, with an actual image of a scaffold created using a bioextrusion system



PROCESS BENEFITS AND DRAWBACKS FDM

PROCESS BENEFITS

1. Low cost per part
2. Flexibility of operation
3. In hot extrusion, post execution alterations are easy because product is still in heated condition
4. Continuous operation
5. High production volumes
6. Many types of raw materials can be used
7. Good mixing (Compounding)
8. Surface finish obtained is good
9. Good mechanical properties obtained in cold extrusion

PROCESS DRAWBACKS

1. Variations in size of product
2. Product limitations because of only one type of cross section can be obtained at a time
3. High initial cost setup

APPLICATIONS OF EXTRUSION-BASED PROCESSES

- Extrusion is widely used in production of tubes and hollow pipes.
- Aluminum extrusion is used in structure work in many industries.
- This process is used to produce frames, doors, window etc. in automotive industries.
- Extrusion is widely used to produce plastic objects.

Process Principle of Polymer Powder Bed Fusion (SLS)

https://youtu.be/rjAJQU_0Uww



Powder Bed Fusion

<https://www.youtube.com/watch?v=A6nRejCsjAc>



Fused Deposition Modeling (FDM) Technology

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

Stereolithography (SLA) Technology

<https://www.youtube.com/watch?v=eKk2vRysioE>

Process Principle of Material Jetting (MJ, DOD)

<https://www.youtube.com/watch?v=uhAigUKJ0ok>