Module 9. Additive Manufacturing

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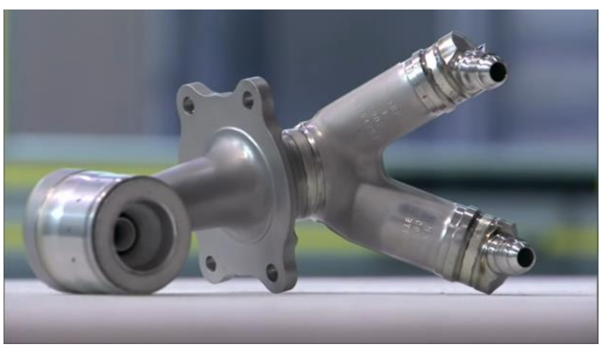
Additive Manufacturing is a process by which a digital 3D design data is used to build up a component in layers by depositing material. Possibilities are unlimited with AM, - High geometrical complexity, - Multiple materials and modulation of material density and composition, - Fast prototyping for testing - Production of small quantities for market evaluation, Personalized products, and many others. There are many giant manufacturers which are using AM as full-scale production, for example GE uses selective laser melting (SLM) to produce fuel nozzles and sensor housings for the GE9X engines; or Align Technologies has been using stereolithography to create millions of customized dental replicas per year, which are used as molds for thermoforming of transparent aligners for orthodontic treatment. In 2014, the US Food and Drug Administration (FDA) approved the use of hip implants made by AM; since then, titanium alloy acetabular cups made by AM have been implanted in more than 50,000 patients; Airbus uses metal 3D printing to produced complex weight-optimized brackets; Nike uses the technology to produce shoe cleats; and now 3D printing found its way to construct houses!



This Module objective:

1. Become familiar with the operating principles of the main AM processes: fused deposition modeling (FDM), stereolithography (SLA), and selective laser melting (SLM).
2. Understand the mechanical properties of polymer and metal parts made by the above AM processes.

Note: The term "***3D Printing***" is often used as a synonym for "***Additive Manufacturing"***; but the latter is more accurate and professional.

The flexibility of AM process is fantastic; However, certain Additive Manufacturing methods may result in anisotropic or less robust structural properties than other manufacturing processes and many processes do not reach the rate of certain mass production techniques, such as injection molding. But, there are many elements which are contributing to the momentum, creative vision, confidence, and success of AM:

- Wide availability of CAD software
- Advanced automation
- A growing availability of printable materials
- Major industry investigations
- Major government investigations
- …

With all these opportunities let's learn the operating principle of the most prominent AM processes.

Additive Manufacturing (AM) refers to a technique which is clearly distinguished from conventional methods of material removal. Some of these techniques are:

- Vat photopolymerization/SLA (material is cured by light-activated polymerization)
- Powder bed fusion/SLS/SLM (energy, typically a laser or electron beam, is used to selectively fuse regions of a powder bed)
- Material extrusion/FDM (material is selectively dispensed through a nozzle and solidifies)
- Material jetting (droplets of build material are jetted to form an object)
- Binder jetting
- Sheet lamination
- Directed energy deposition

There are different terminologies in AM and sometimes they are used interchangeably. In this module we categorize the additive manufacturing techniques based on its mechanism as:

Extrusion: **FDM** (Fused Deposition Modeling) aka **FFF** (Fused Filament Fabrication)

Photopolymerization: **SLA** (**S**tero**L**ithogr**A**phy) aka Optical Fabrication, Photo-solidification, or Resin Printing

Powder Bed Fusion: **SLS/SLM** (Selective Laser Melting / Sintering) aka **DMLS** (Direct Metal Laser Sintering)

And based on the applications as:

- **AM of polymers by:**
    - FDM/FFF
    - SLA
- **AM of metals by:**
    - SLM/SLS/ DMLS

The following sections review each of these techniques briefly.

AM of polymers by Fused Deposition Modeling (FDM) also known as Fused Filament Fabrication (FFF):

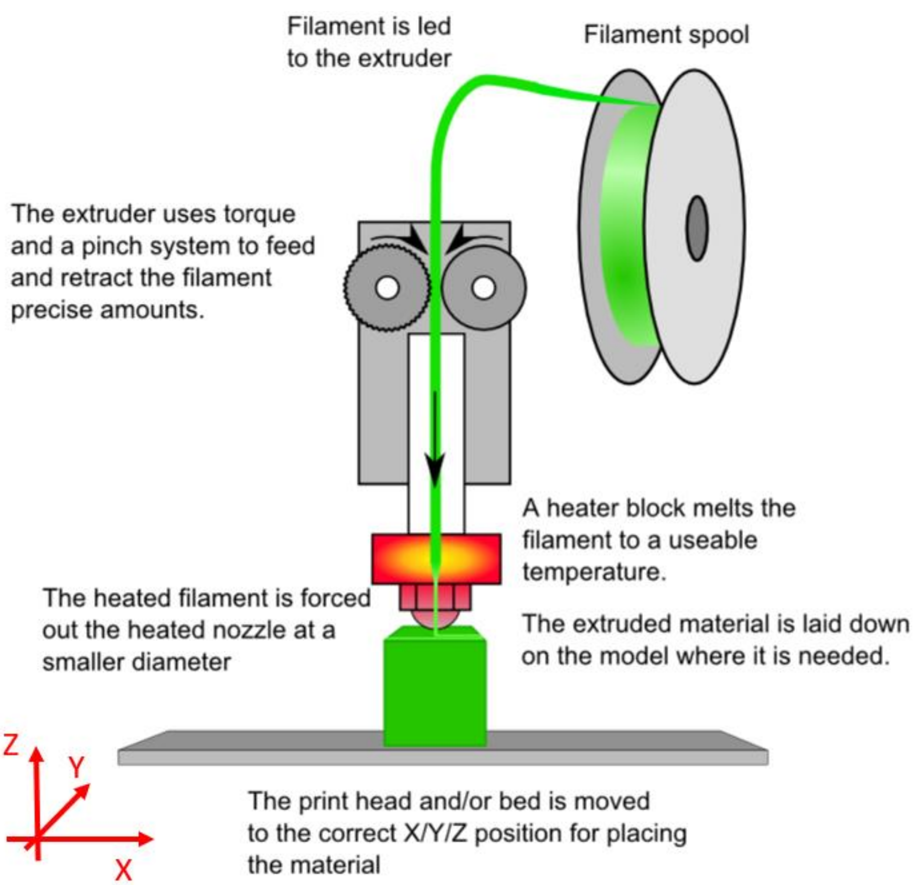


Image source: https://reprap.org/wiki/Fused_filament_fabrication

In **FFF** (fused filament fabrication) a tool deposits a filament of a material on top of the same material, making a joint (by heat or adhesion). The term Fused Filament Fabrication is equivalent to **FDM** (Fused Deposition Modeling) and is used interchangeably. Objects printed with FFF are layered, so they have a grain like wood. Even when printed with an infill rate of 100%, such objects are not quite as strong (in some directions) as others. An interlocking infill pattern seems to give more strength.

AM of polymers by Stereolithography (SLA)

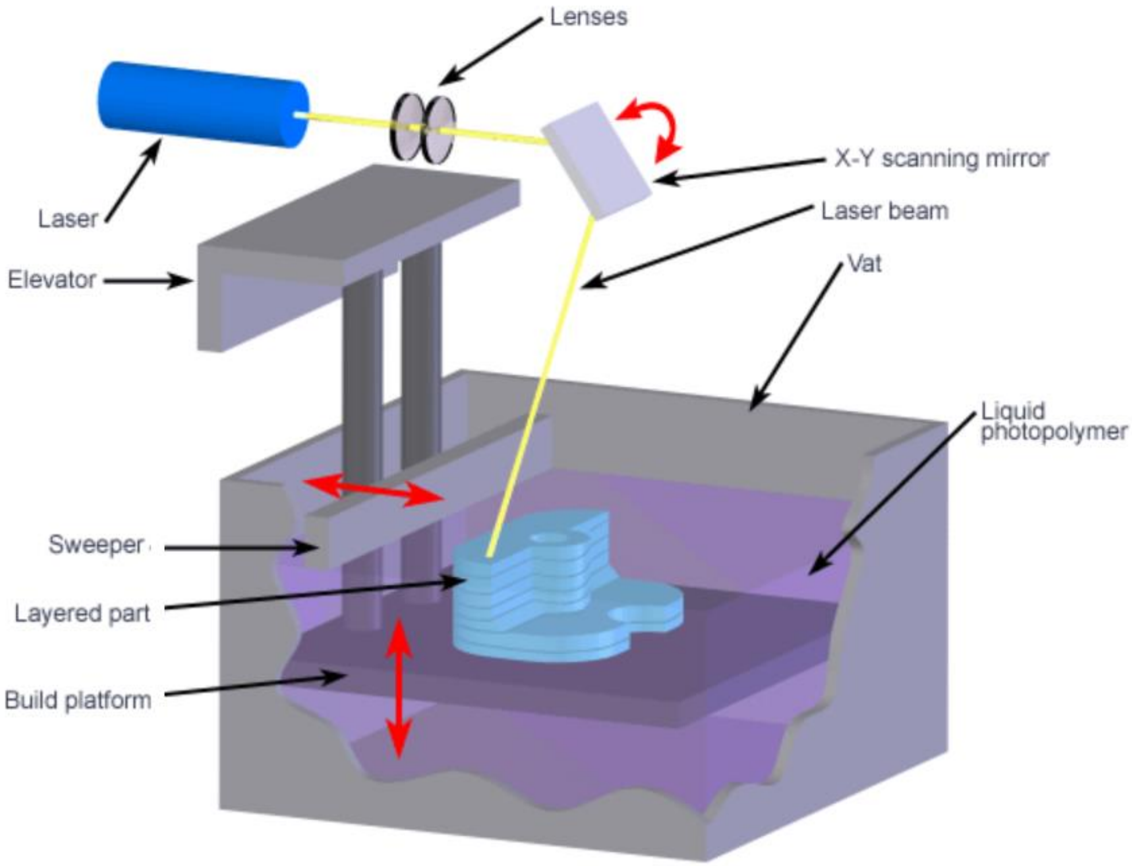
Stereolithography (SLA), also known as Optical Fabrication, Photo-solidification, or Resin Printing is a form of 3D printing technology used for creating models, prototypes, patterns, and production parts in a layer by layer fashion using photochemical processes by which light causes chemical monomers[1] to link together to form polymers.

Stereolithographic models are used in medicine for creating accurate 3D models of various anatomical regions of a patient, based on data from computer scans. Medical modelling involves first acquiring a CT or MRI.

SLA works by using a high-powered laser to harden liquid resin that is contained in a reservoir to create the desired 3D shape. This process converts photosensitive liquid into 3D solid plastics in a layer-by-layer fashion.

The following figure shows a schematic of SAL mechanism. SLA uses a low-power, highly focused UV laser to trace out successive cross-sections of a three-dimensional object in a vat of liquid photosensitive polymer. As the laser traces the layer (controlled by the orientation of the mirror), the polymer solidifies, and the excess areas are left as liquid. When a layer is completed, a leveling blade (sweeper) is moved across the surface to smooth it before depositing the next layer. The platform is lowered by a distance equal to the layer thickness (typically 50-100 micron), and a subsequent layer is formed on top of the previously completed layers. This process of tracing and smoothing is repeated until the build is complete. Once complete, the part is elevated above the vat and drained. Excess polymer is rinsed away from the surfaces. In many cases, a final cure is given by placing the part in a UV oven. After the final cure, supports are cut off the part and surfaces are polished and sanded.

1-A monomer is a molecule that can be reacted together with other monomer molecules to form a larger polymer chain or three-dimensional network in a process called polymerization.

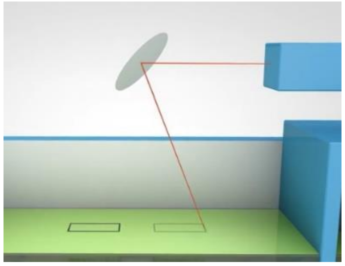


Source: https://www.custompartnet.com/wu/stereolithography

In summary, every standard SLA 3D printer is composed of six primary sections:

- A tank filled with a liquid plastic resin.
- A platform immersed in a tank, which can move up and down according to the printing process.
- A high-powered, ultraviolet (UV) laser
- Mirror with two rotational degree of freedom to orientate the laser beam to a specific x and y coordinate according to the G-Code (printing process)
- A sweeper blade which is moved across the surface to smooth a layer before depositing the next layer.
- A computer interface, which manages both the platform and the laser movements.

Here is a short animation of the process:



Here is a short video which explain a SLA machine, and the advantages of SLA

Most of hearing aid are made by SLA, and the shape/geometries of it can be personalized to fit an individual ear:

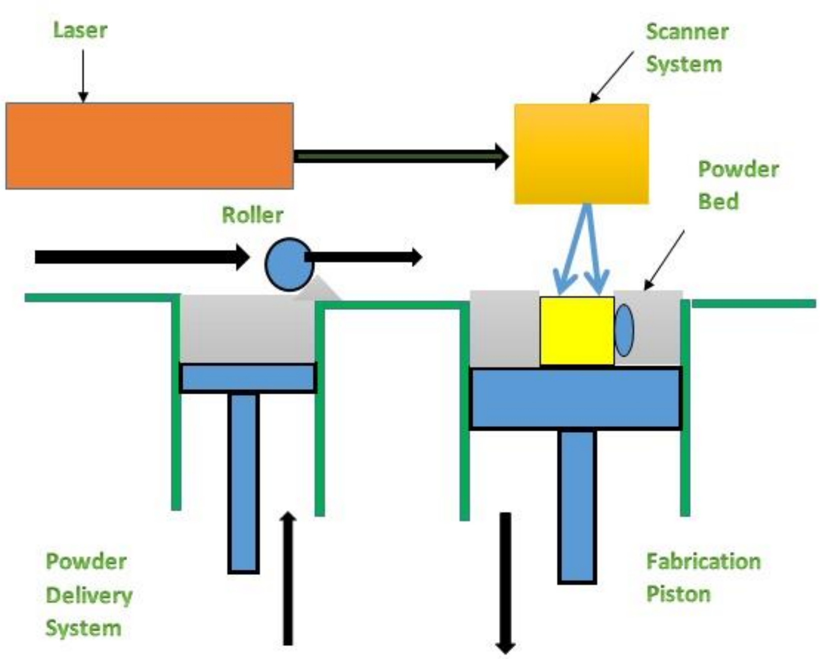
The rate and the accuracy of SLA parts are limited by key parameters in SLA. As mentioned above, in SLA, light is used to crosslink chains of molecules into solid polymers, usually by pointing a laser into a bath of liquid resin to build up a structure layer by layer. Thus, the rate of SLA is limited by the rate of transmitting energy to the resin to crosslink the molecules, laser power, the scanning speed of the galvanometers positioning the laser, and the time to coat a new resin between every layer.

The precision/resolution is most crucially influenced by the laser focal spot size (laser spot diameter). The material crosslinks wherever a certain energy threshold is met, and the smaller the laser spot diamter, the smaller the created feature.

AM of metals by SLM/SLS/ DMLS:

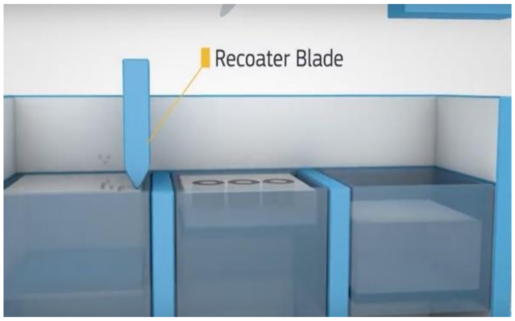
SLM is great when it comes to reducing weight while maintaining the strength of a part, and often pays off in expensive, low volume applications such as aerospace. The parts made with SLM range from simple brackets to complex turbine parts. SLM is a relatively slow and expensive process. It is rarely used for fast prototypes.

The following figure shows a schematic of SLS mechanism. Selective Laser Sintering (SLS) belongs to the Powder Bed Fusion family. In SLS, a laser selectively sinters the particles of a powder, fusing them together and building a part layer-by-layer. First a thin layer of powder is spread over the build platform. A laser then scans the contour of the next layer and selectively sinters (fuses together) the particles of the powder. The entire cross section of the component is scanned, so the part is built solid. When the layer is complete, the build platform moves downwards and the blade re-coats the surface. The process then repeats until the whole part is complete. After printing, the parts are fully encapsulated in the unsintered powder. The parts are then cleaned with compressed air or other blasting media and are ready to use or further post process. The remaining unsintered powder is collected and can be reused.



Source: https://tajagna-youthclub.com/2019/04/11/selective-laser-sintering-sls-3d-printing-process/tajagna/4619/

Here is a short animation of the process:



The advantages of the technology are:

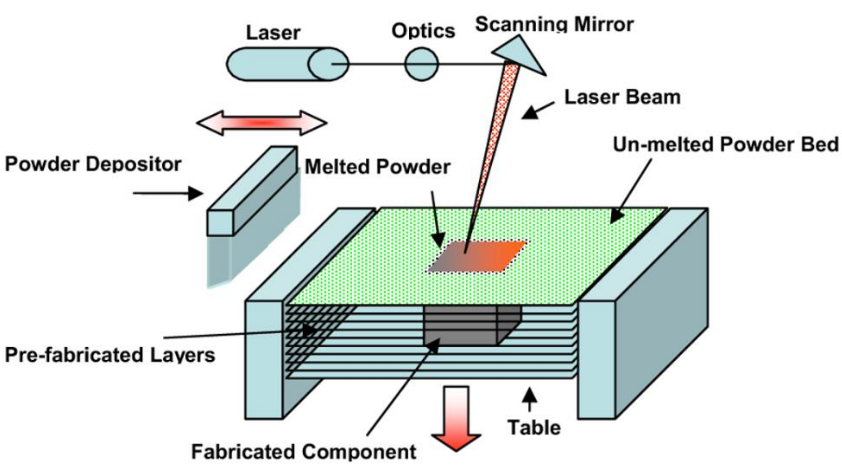
- SLS parts have good, isotropic mechanical properties.
- SLS requires no support, so designs with complex geometries can be easily produced. The unsintered powder provides the part with all the necessary support.

The disadvantages of the technology are:

- Only industrial SLS systems are currently widely available.
- SLS parts have a grainy surface finish and internal porosity, so if a smooth surface or is required, then post-processing is needed.
- Large flat surfaces and small holes cannot be printed accurately with SLS, as they are susceptible to warping and over-sintering.

References: https://www.3dhubs.com/knowledge-base/introduction-sls-3d-printing

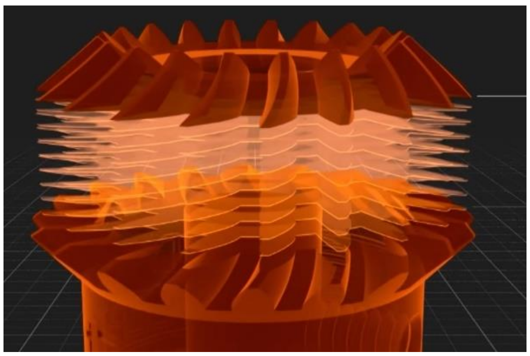
Here is another schematic of SLS mechanism:



Source: https://www.semanticscholar.org/paper/HIGH-DENSITY-SELECTIVE-LASER-MELTING-OF-WASPALOY-%C2%AE-Morganti-umtaz/d650e1db9790a3675373a8ab3629495842ae3198

The key process component in SLS:

- Laser power
- Laser scan speed
- Laser scan pattern
- Particle size
- Packing density
- Layer thickness
- Bed temperature



Watch behind the seen in GE, using AM:

Currently, the SLS machines are not as accessible as the FDM and SLA machines; they are mainly large, expensive and are used mainly in industrial level; but the good news is, they are coming, and it is not unreasonable to think, soon the desktop one will be available, and maybe you buy one for your startup company or making stuff at home! Watch this, here is the start:

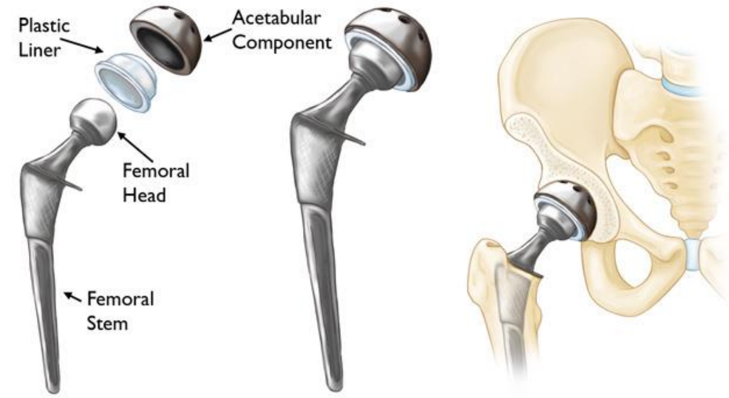
While SLM provides a better resolution and stronger parts than FDM and SLA; also with SLM it is possible to create parts out of metal that have intricate details, undercuts and other traditionally challenging geometries; however this technique has some disadvantages:

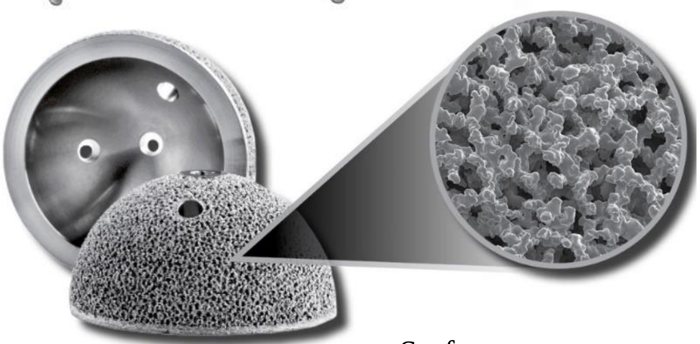
- Complexity of working with powder (handling and storage of powder is difficult, it is flammable, it has inhalation risks, and vulnerable to Oxidation or Contamination)
- The process requires higher energy; using the same material, these are a rough estimation of required energy:
    - SLA: 0.1-1 W for photopolymerization
    - FDM:1-10W for melting the filament
    - SLS:100-1000W for melting the powder
- Postprocessing (the pain of removing and cleaning the powder)
-

Materials which SLS can be applied to:

Powder fusion / selective laser sintering can be applied to a variety of materials, including metals (ferrous and non-ferrous), ceramics, composites, and polymers.

Quality of life built with Additive Manufacturing:





Surface texture promote better bone attachment.

Read more here: http://www.arcam.com/solutions/orthopedic-implants/

Summary

From the additive manufacturing discussed above, only Fused Deposition Modeling (FDM) and Stereolithography are limited to polymers. FDM used extruded plastic spool stock that is fed through a heated printer head to write the plastic layer by layer. Stereolithography requires a photopolymer to initiate a polymerization reaction. The Selective Laser Sintering (SLS) method can be used to fuse plastics, and with enough laser intensity, metals as well. The powder can be a plastic, metal, or even ceramic.

One downside to most additive manufacturing techniques lies in the quality of the surface finish. Stereolithography is likely the additive process with the highest resolution, but it requires post-print curing. Powder bed techniques leave a rough finish, and fused deposition modeling may leave unsightly lines. Additionally, the porosity inherent in these techniques reduce the strength of the finished part.

Another place where additive is lacking is the production rate. For custom or complex components, additive manufacturing may be an irreplaceable technology, but it cannot compete on the production scale of other established methods such as injection molding for simple mass-produced parts.