Additive Manufacturing

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1. Rapid Prototyping
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Formative manufacturing

In formative methods, the final geometry of the part is achieved

(1) Either by pouring the molten metal into the mold (**casting processes** such as sand, lost foam, or lost wax casting etc.) or

(2) By plastically deforming the bulk of material in its solid state (**bulk deformation processes**)

such as

- forging,
- rolling,
- extrusion, etc ..

Subtractive manufacturing

- **Subtractive manufacturing is an umbrella term**
- for various controlled machining and material removal processes
- that start with solid blocks, bars, rods of plastic, metal, or other materials
- that are **shaped by removing material** through

✔ cutting,

✔ boring,

✔ drilling, and

✔ grinding.

Additive manufacturing

- **Additive manufacturing** **uses data computer-aided-design (CAD) software or 3D object scanners** to direct hardware to deposit material, layer upon layer, in precise geometric shapes.
- As its name implies, additive manufacturing adds material to create an object.
- By contrast, when you create an object **by traditional** means, it is **often necessary to remove material** through milling, machining, carving, shaping or other means.

Additive manufacturing

- Although the terms "3D printing" and "rapid prototyping" are casually used to discuss additive manufacturing, each process is actually a subset of additive manufacturing.
- While additive manufacturing seems new to many, it has actually been around for several decades.
- In the right applications, **additive manufacturing delivers** a perfect trifecta of improved performance, complex geometries and simplified fabrication.
- As a result, opportunities abound for those who actively embrace additive manufacturing.

Classification of manufacturing techniques

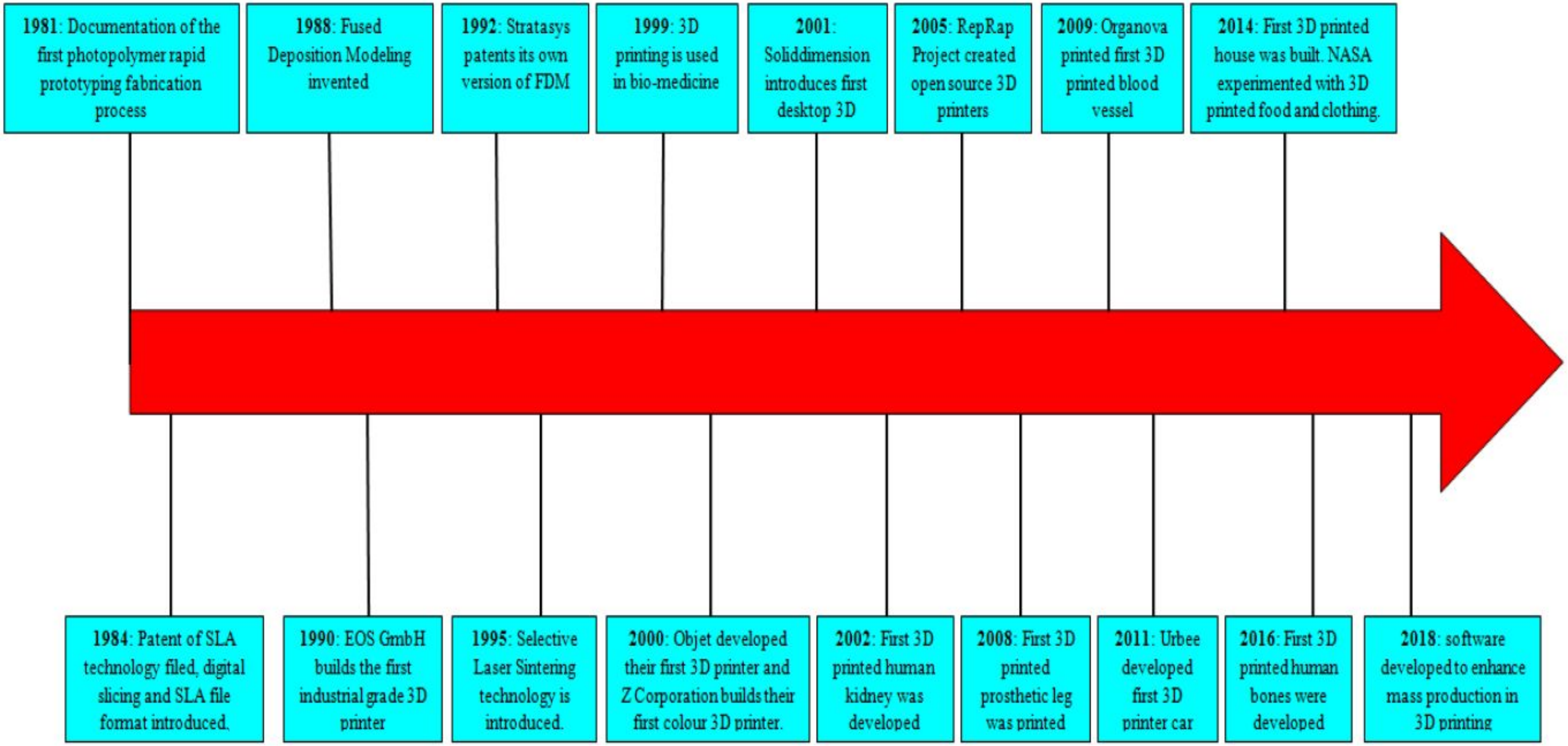
Most manufacturing techniques can be categorized into three groups.

· **Formative manufacturing:** best suited for high volume production of the same part, requiring a large initial investment in tooling (molds) but then being able to produce parts quickly and at a very low unit price.

· **Subtractive manufacturing:** lies in between formative and additive, is best suited for parts with relatively complex as well as simple geometries, produced at low-mid volumes, typically made from functional materials.

· **Additive manufacturing:** best suited for low volume, complex designs that formative or subtractive methods cannot produce, or when a unique one-off rapid prototype is required.

History of Additive manufacturing



History of AM

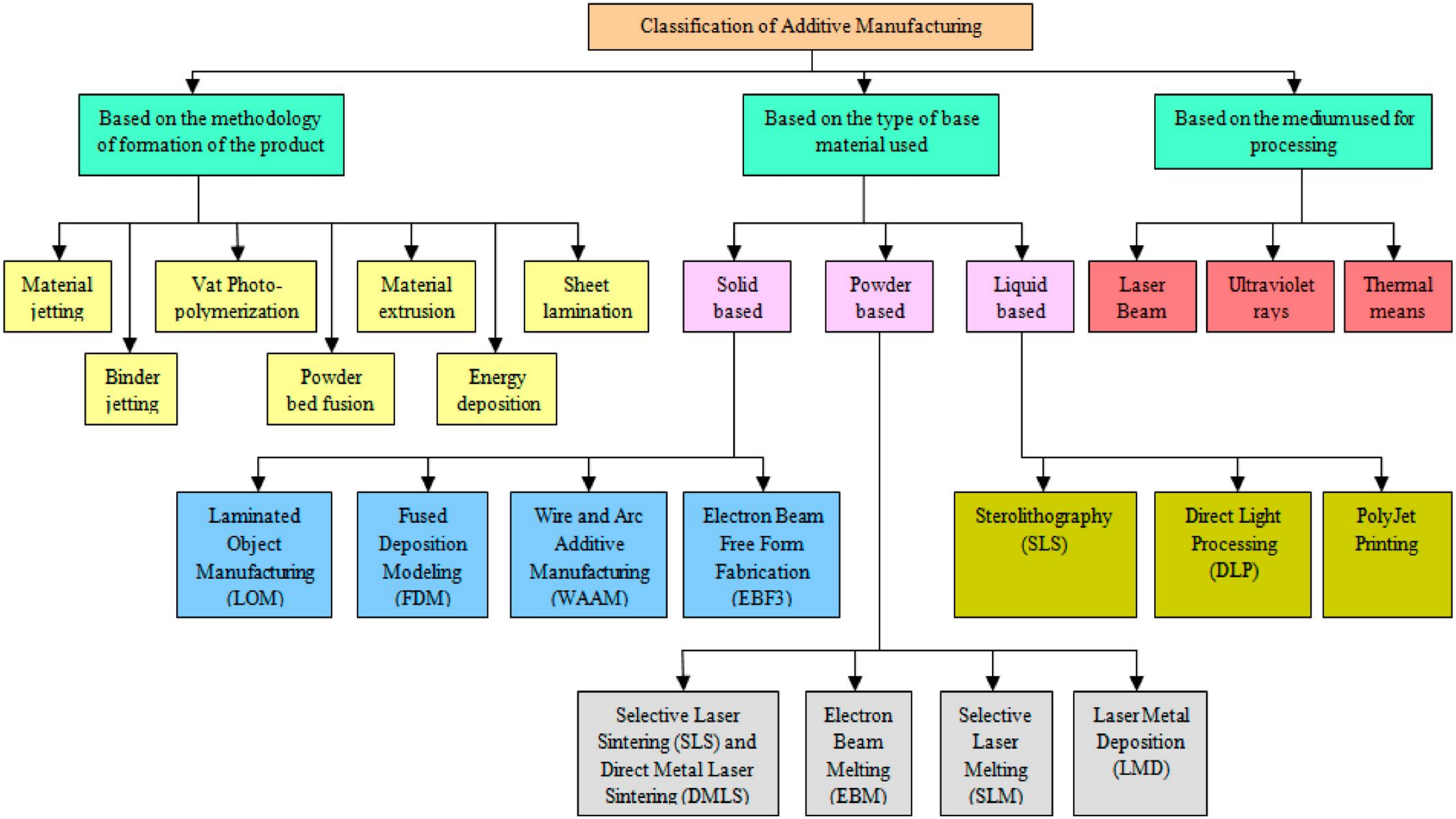
https://doi.org/10.3390/polym13050753

3D Printing Process

3 D Printing Process

https://www.researchgate.net/publication/334544502_CAN_HUMAN_BEINGS_PRODUCE_EVERYTHING_THE_LIMITS_OF_THE_3D_PRINTERS

Classification of Additive Manufacturing Processes



Classification of Additive Manufacturing Processes

Additive Manufacturing Material Groups

❑ ***Polymers***

- ***Polymers, such as plastics, come in many different forms, and their diversity of properties sees them used for a wide range of applications. Polymers are found in everything from adhesives to biomedical devices.***

- ***Today, the polymer industry is larger than the steel, aluminum, and copper industries combined. Polymers in additive manufacturing generally come in three different forms: filament, resin, and powder.***

- ***Polymers in 3D printing are generally divided into thermoplastics and thermosets.***

- ***They differ mainly in their thermal behavior.***

Thermoplastics and thermosets used in 3D printing

Thermoplastics

- Thermoplastics can be melted and solidified over and over again while generally retaining their properties. Both traditional injection molding and the FFF printing processes make use of thermoplastics by heating solid thermoplastic to a malleable state and injecting or extruding it into a die or onto a build platform where it then solidifies.
- ABS (Acrylonitrile butadiene styrene), PLA (polylactide), PC (polycarbonate), and Polyamide (Nylon) are the commonly used thermoplastic materials. Common thermoplastic products include plastic bottles, LEGO bricks, and food packaging.

Thermosets

- Unlike thermoplastics, thermosets do not melt. Thermosets typically start as viscous fluid and are cured to become solid. Curing can occur via heat, light exposure, or mixing with a catalyst. Once solid, thermosets cannot be melted and will lose structural integrity when subjected to high temperatures. Epoxy, polyurethane, silicone resin, polyimide are commonly used thermosets.

Additive Manufacturing Material Groups

- *The SLA/DLP and Material Jetting processes use photopolymer thermosets that harden when exposed to a laser or UV light. Common thermoset products include two-part epoxies, bowling balls, and high-temperature components, like the knobs on a stovetop.*

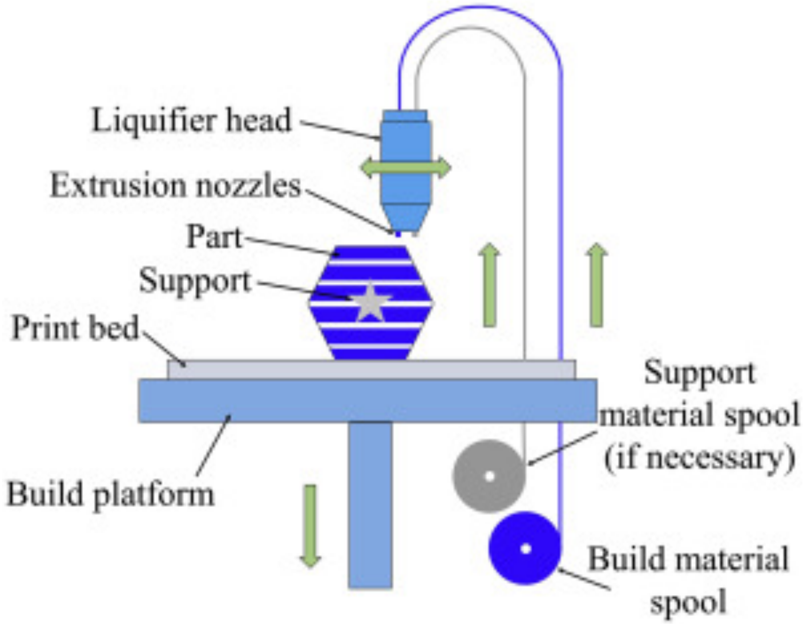
Metal

- *Unlike polymers, which are used in various forms (solid filaments, powder, resins), metal additive manufacturing almost exclusively uses powders. Metal printing allows for high-quality, functional, and load-bearing parts to be produced from various metallic powders.*

- *Particle size distribution, shape, and flowability (the collective forces acting on individual particles as they flow) are essential properties that govern how appropriate a metal powder is for 3D printing.*

Material Extrusion

- *Material extrusion prints using a string of solid thermoplastic material (filament), pushing it through a heated nozzle and melting it in the process. The printer deposits the material on a build platform in a predetermined path, where the filament cools and solidifies to form a solid part.*



Material Extrusion Process

Material Extrusion

- *A spool of filament is loaded into the printer and fed through to the extrusion head. Once the printer nozzle has reached the desired temperature, a motor drives the filament through the heated nozzle melting it.*

- *The printer then moves the extrusion head around, laying down melted material precisely, where it cools down and solidifies. Once a layer is complete, the build platform moves down, and the process repeats, building up the part layer-by-layer.*

- *Many parameters can be adjusted on most FFF (Fused Filament Fabrication) machines to achieve an accurate print. Build speed, extrusion speed, nozzle temperature control layer height, number of shells, feed rate, travel feed rate, print temperature, filament diameter, and nozzle diameter.*

Different AM Processes and relevant process physics

Material Extrusion

- ***At a fundamental level, nozzle diameter and layer height define the resolution of an FFF printed part. While all parameters define the dimensional accuracy of a part, smaller nozzle diameter and lower layer height are generally seen as the solutions for parts where a smooth surface and higher level of detail are required.***

- ***On average, desktop printers usually offer a 200 x 200 x 200 mm build chamber. Larger industrial machines can offer to build chambers as large as 1000 x 1000 x 1000 mm. Breaking a design down into components that can be assembled after printing is often the best solution for huge parts.***

- ***Common applications involve investment casting patterns, electronics housings, jigs and fixtures, and several other household and industrial applications.***

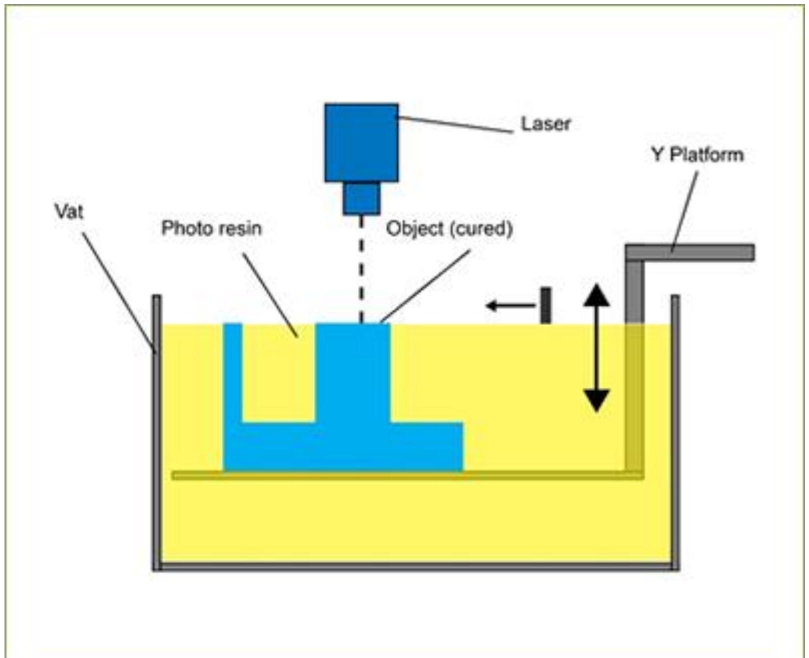
Fused Filament Fabrication (FFF) machine

Fused Filament Fabrication (FFF) machine

Different AM Processes and relevant process physics

Vat

- *Vat Polymerization technologies utilize a **photo-polymer resin** in a vat that is **cured by a light source**. The most common forms of Vat Polymerization are **SLA (Stereolithography) and DLP (Direct Light Processing).***
- *A photopolymer or light-activated resin is a polymer that **changes its properties** when **exposed to light**, often in the ultraviolet or visible region of the electromagnetic spectrum.*



Vat Photopolymerization Process

https://www.lboro.ac.uk/research/amrg/about/the7categoriesof additivemanufacturing/vatphotopolymerisation/

Vat Photopolymerization

- *The process uses mirrors, known as galvanometers or galvos (one on the x-axis and one on the y-axis) to rapidly aim a laser beam across a vat, the print area, curing and solidifying resin as it goes along. This process breaks down the design, layer by layer, into a series of points and lines given to the galvos as a set of coordinates.*

Direct Light Processing :

- *DLP follows a near-identical method of producing parts when compared to SLA. The main difference is that DLP uses a digital light projector screen to flash a single image of each layer all at once. Because the projector is a digital screen, the image of each layer is composed of square pixels, resulting in a layer formed from small rectangular bricks called voxels.*

- *DLP can achieve faster print times than SLA, as an entire layer is exposed simultaneously, rather than tracing the cross-sectional area with a laser pointer.*

Vat Photopolymerization

SLA vs. DLP :

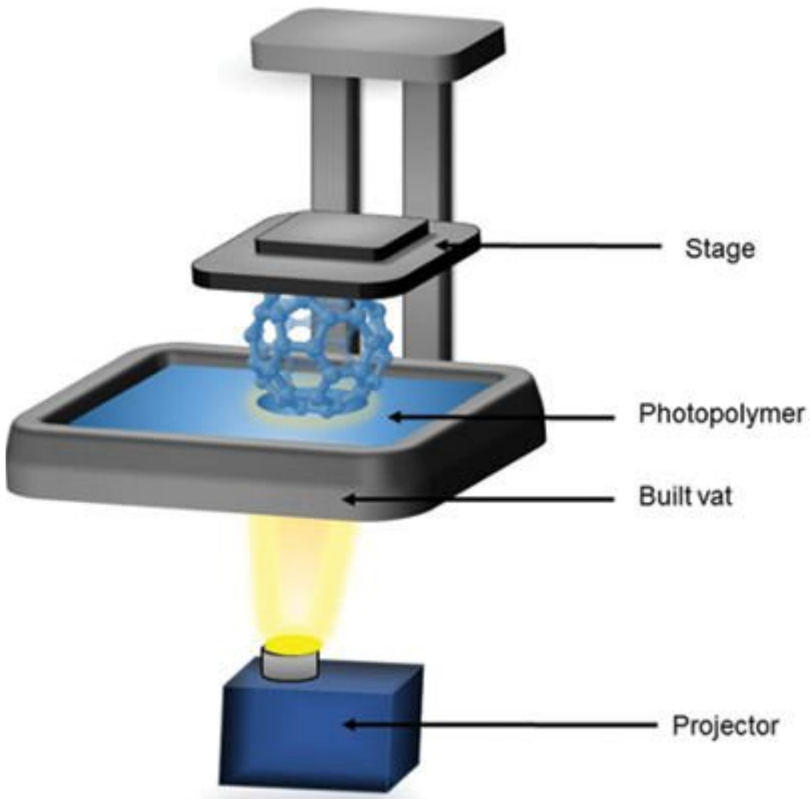
- The fundamental difference between SLA and DLP is the light source each technology uses to cure the resin. SLA printers use a point laser compared to the voxel approach that DLP printers use.

- The downside to SLA using a point laser is that it takes longer to trace the cross-section of a part than DLP printers which are capable of exposing the cross-section in a single flash (depending on part size). This makes DLP faster than SLA when printing an identical part.

- Unlike FFF, most printer parameters on Vat Polymerization machines are fixed and cannot be changed. Typically, the only operator inputs are part orientation/support location, layer height, and material, all specified at the slicing stage. Most printers auto-adjust settings based on the type of material used.

Different AM Processes and relevant process physics

Vat Photopolymerization



DLP

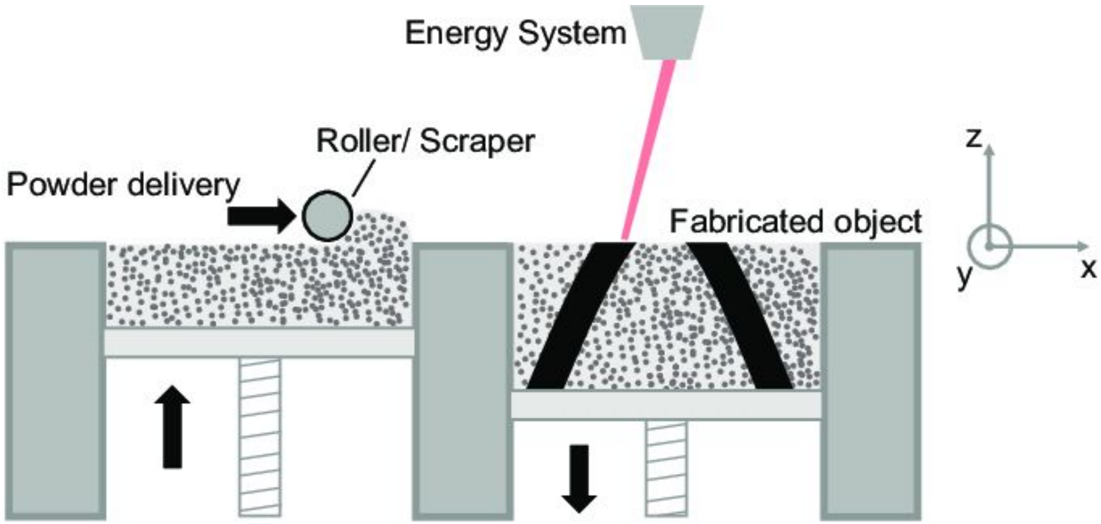
Comparison between SLA and DLP

https://www.3dsourced.com/3d-printing-technologies/digital-light-processing-dlp/

Different AM Processes and relevant process physics

Powder Bed Fusion

- ***Powder Bed Fusion technologies utilize a thermal source to induce fusion between powder particles at a specific location of the build area to produce a solid part. Most Powder Bed Fusion technologies employ mechanisms for applying and smoothing powder as a part is constructed, resulting in the final component being encased in powder.***



Selective Laser Sintering Process

Powder Bed Fusion

Selective Laser Sintering:

- The SLS process begins with a bin of the polymer powder being heated to a temperature just below the polymer's melting point. A recoating blade deposits a very thin layer of the powdered material (typically 0.1 mm) onto a build platform.

- A CO_2 laser beam then starts to scan the surface. The laser selectively sinters the powder and solidifies a cross-section of the part. Like SLA, the laser is focused on the correct location by a pair of galvanometers. When the entire cross-section is scanned, the building platform moves down one layer thickness in height.

- The recoating blade deposits a new layer of powder on top of the recently scanned layer, and the laser starts to sinter the successive. Cross-section of the part onto the previously solidified cross-sections. This process is repeated until all parts are entirely manufactured.

Different AM Processes and relevant process physics

Powder Bed Fusion

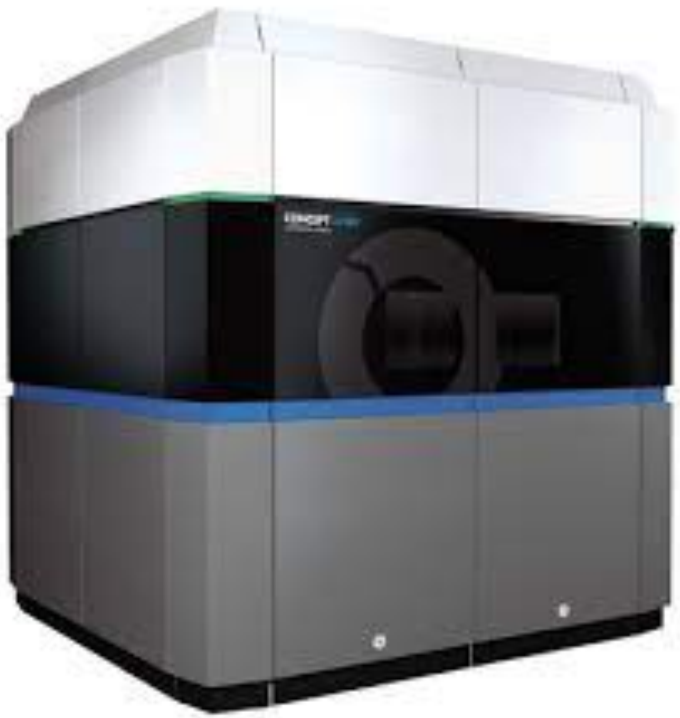
- ***A range of parameters governs how well a part will print on an SLS machine. Laser spot size and layer height define a printed part's accuracy and surface finish.***

- ***Powder particle geometry and size also play a significant role in defining the properties of a part. Finer powders will result in a smoother part surface but present issues with handling and spreading during the recoating stage of the print. While more straightforward to handle, Coarser powders will negatively affect the surface finish and achievable feature sizes.***

- ***SLS parts are also susceptible to shrinkage and warping during printing. As each layer is sintered, it fuses with the layer below as it cools. This cooling causes the newly printed layer to shrink, pulling up the underlying layer. The part can curl up and clash with the recoater during the powder spreading stage in the worst-case scenario.***

Different AM Processes and relevant process physics

Powder Bed Fusion



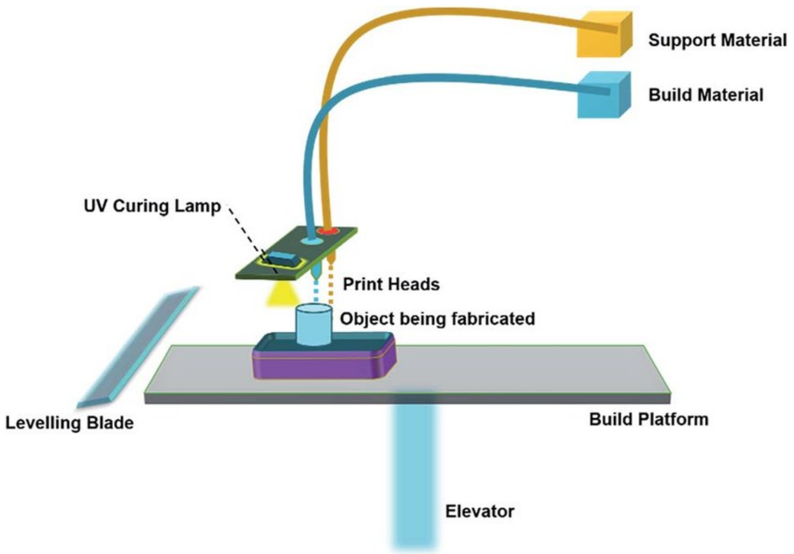
Powder Bed Fusion Machine

Manufacturing of a part

https://www.makepartsfast.com/ge-introduces-first-laser-powder-bed-fusion-additive-manufacturing-system/

Material Jetting

Material Jetting is often compared to the 2D ink printing process. Utilizing photopolymers or wax droplets that cure when exposed to light, parts are built up one layer at a time. The nature of the Material Jetting process allows for different materials to be printed in the same part. This is often utilized by printing support structures from a different material during the build phase.



Material Jetting Process

DOI:10.1039/C8RA03194K

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Material Jetting

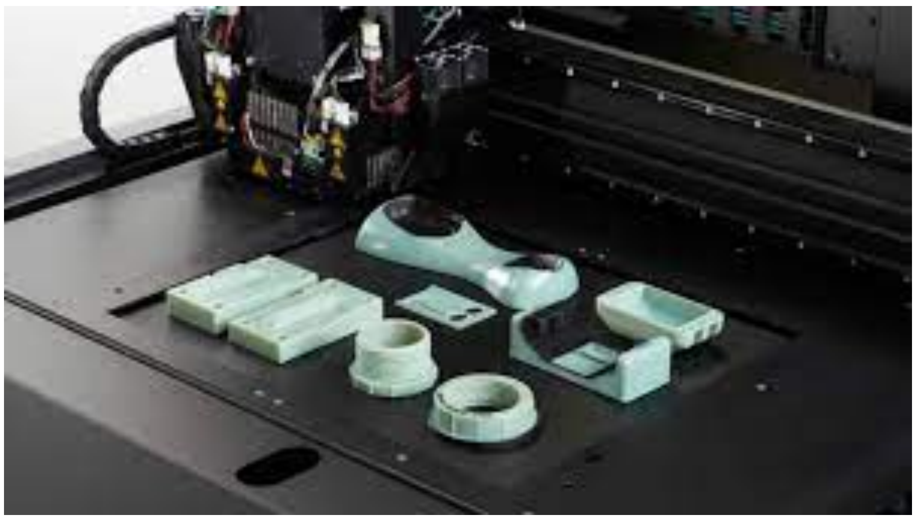
- *Jet droplet size (directly related to printhead jet diameter) and layer height influence the surface finish and minimum feature size of a part. It can produce parts with layer heights as low as 16 microns, resulting in very smooth surfaces. One of the major pros of Material Jetting is that all parts are printed in 2 different materials; one for the primary build material and the second as dissolvable support.*

- *This means that unlike other 3D printing methods, where support must manually be cut away from the part, support is dissolved and easily removed with light agitation. When the post-processed correctly, there is no indication of support at all.*

- *Material Jetting is considered the most accurate form of 3D printing. Warping and shrinkage are not present because there is no heat involved in the printing process.*

Different AM Processes and relevant process physics

Material Jetting



Material Jetting Process

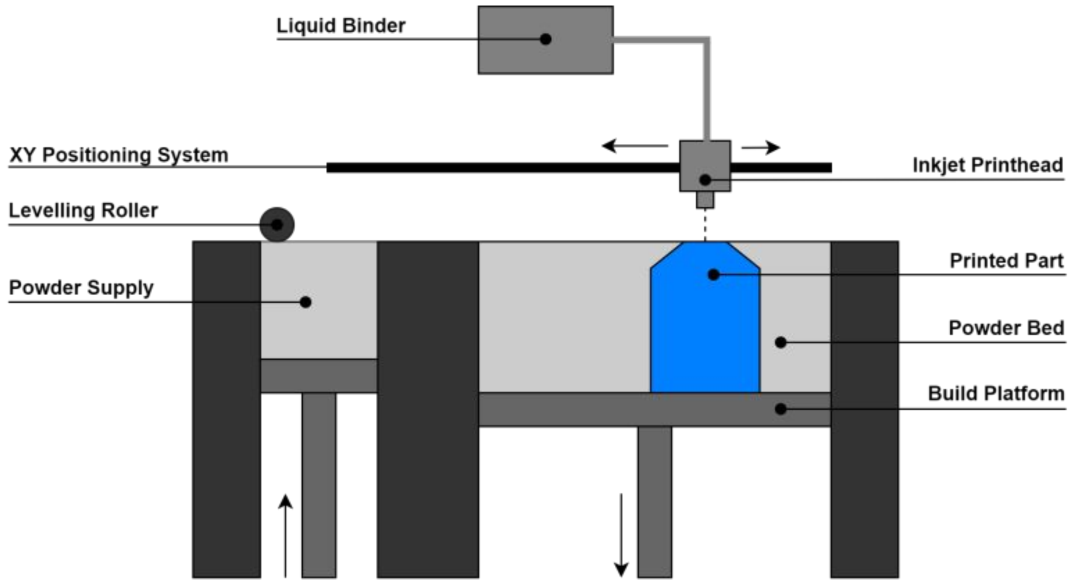
Commercial Printer

https://www.makepartsfast.com/ge-introduces-first-laser-powder-bed-fusion-additive-manufacturing-system/
https://www.hubs.com/knowledge-base/how-design-parts-material-jetting-3d-printing/

Different AM Processes and relevant process physics

Binder Jetting

Binder Jetting is a versatile 3D printing technology used for various applications. Binder Jetting is the process of depositing a binding agent onto a powder bed to form a part, one layer at a time. These layers bind to one another to form a solid part. Binder Jetting can be separated into two categories: sand printing and metal printing.



Binder Jetting Process

https://en.wikipedia.org/wiki/File:BinderJetting.svg

Binder Jetting

- *Binder Jetting is an effective combination of SLS and Material Jetting characteristics, using powdered material and a printhead that jets a binder agent to create solid parts.*

- *The accuracy and surface finish of the components depend upon the specified layer height, the jetted droplet size, and the powder size and geometry. Like SLS, Binder Jetting does not require support structures to be printed as parts are surrounded by powder during the printing process. This reduces post-processing times and the amount of material consumed per print.*

- *One of the significant advantages of Binder Jetting is that the process does not use any heat, meaning parts don't suffer from the residual stresses. Because the process does not rely on a heat source to create parts, operating costs are low and large parts can be printed.*

Binder Jetting

- ***One of the limitations of the Binder Jetting process is part strength. Even after applying a strengthening infiltrant, parts exhibit limited strength and elongation at break properties compared to claims made with Powder Bed Fusion.***

- ***Shrinkage issues are related to the secondary infiltration or sintering processes. Thermal shrinkage relating to the infiltration process is often unpredictable and non-uniform during the cooling stage of the process.***

- ***The majority of the applications of this technology involve full-color models, sand casting, and functional metal parts.***

Different AM Processes and relevant process physics

Binder Jetting

Binder Deposition

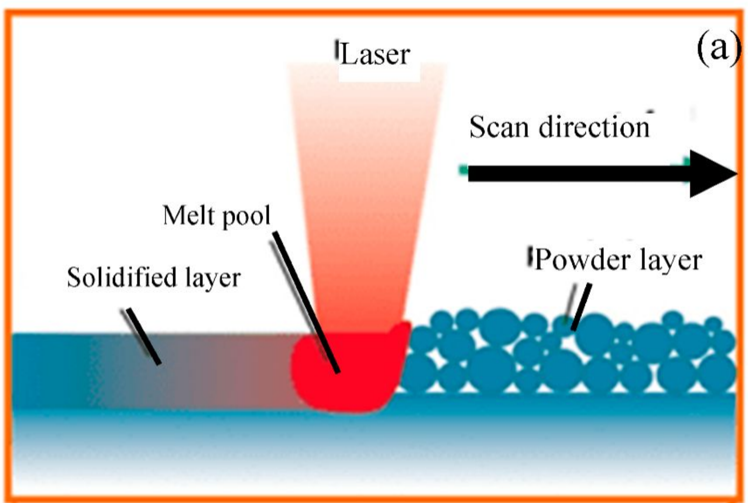
Industrial Binder Jet Printer

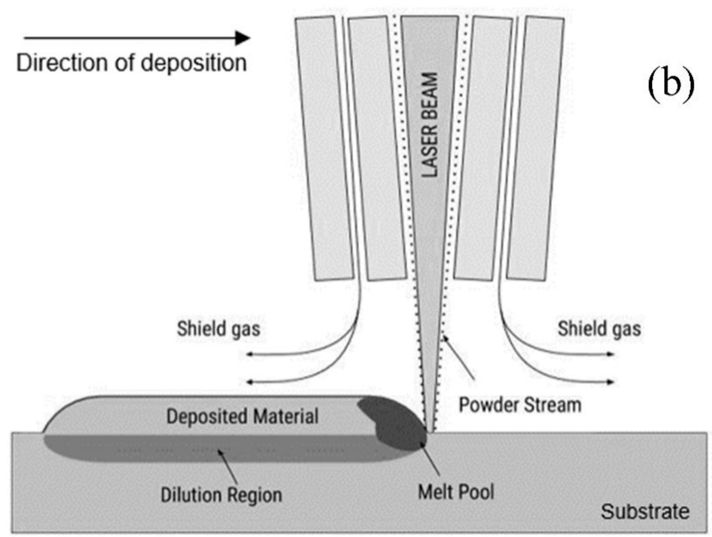
https://amfg.ai/2018/04/27/top-5-binder-jetting-machines/
https://www.exone.com/en-US/Resources/case-studies/what-is-binder-jetting

Different AM Processes and relevant process physics

Direct Energy Deposition

Directed Energy Deposition (DED) allows for the creation of objects by melting the material (most frequently used for metals such as titanium, aluminum, stainless steel, or copper) in powder or as a wire with a focused energy source as a nozzle deposits it on a surface In a DED printer; the nozzle head moves around a fixed object for depositing the material in specific locations.





Direct Energy Deposition

https://doi.org/10.3390/app9163316
doi:10.1016/b978-0-12-819724-0.00008-2

Direct Energy Deposition

- The DED process is known by other names, including Laser Engineered Net Shaping (LENS), Direct Metal Deposition (DMD), Electron Beam Additive Manufacturing (EBAM), and Directed Light Fabrication, and 3D Laser Cladding, depending on the exact application or method used.
- Layers are typically 0.25mm to 0.5mm thick. The cooling times for materials are fast at around 1000-5000 °C per second. The cooling time affects the final grain structure, although overlapping in the material can cause re-melting, which creates a uniform but alternating microstructure.
- Almost any weldable metal can be additively manufactured using DED, including aluminum, Inconel, niobium, stainless steel, tantalum, titanium and titanium alloys, and tungsten.

Direct Energy Deposition

- *According to ASTM International: "DED has the ability to produce relatively large parts (build volume > 1000 mm³) requiring minimal tooling and relatively little secondary processing. In addition, DED processes can be used to produce components with composition gradients, or hybrid structures consisting of multiple materials having different compositions and structures."*
- *This makes the process ideal for producing machined parts from expensive or hard-to-cut metals. As a result, DED lends itself to the production of items such as aerospace brackets, tanks, and ribs. Near-Net-Shape part manufacture tends to be used primarily within the aerospace, defense, power, and marine sectors.*

Different AM Processes and relevant process physics

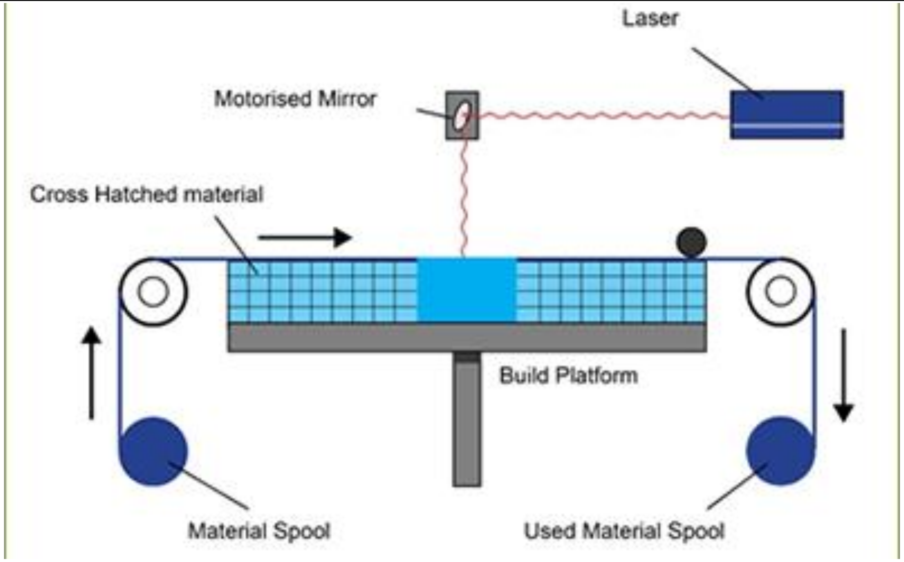
Direct Energy Deposition

Metal Deposition Process

https://3dprint.com/238130/restoring-industrial-components-with-directed-energy-deposition-saves-time-and-costs/

Sheet Lamination

Sheet lamination is an additive manufacturing methodology where thin sheets of material (usually supplied via a system of feed rollers) are bonded together layer-by-layer to form a single piece cut into a 3D object. Laminated object manufacturing (LOM) and ultrasonic consolidation (UC) are both examples of sheet lamination techniques.



Process

https://www.lboro.ac.uk/research/amrg/about/the7categoriesofadditivemanufacturing/sheetlamination/

Sheet Lamination

- *Sheet lamination can use various materials such as paper, polymer, and metal - but each requires a different method to bind the sheets of material together. Paper sheets are usually attached using heat and pressure to activate a layer of activated adhesive pre-applied to the sheets.*

- *For specific polymers, the same application of heat and pressure is used to melt the sheets together. Metal sheets are bound with ultrasonic vibrations under pressure (i.e., ultrasonic welding).*

- *Sheet lamination is one of the less accurate AM methods; manufacturers use it as a fast and low-cost way to 3D print-non-functional prototypes, casting molds, and other simple designs out of easily handled materials. Because it allows build materials to be swapped out in the middle of printing, sheet lamination is also used to make composite materials.*

https://www.plm.automation.siemens.com/global/en/our-story/glossary/sheet-lamination/

Different AM Processes and relevant process physics

Sheet Lamination

- ***Advantages:***

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

- ***Disadvantages:***

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

Different AM Processes and relevant process physics

Sheet Lamination

Metal Deposition Process

https://3dprint.com/238130/restoring-industrial-components-with-directed-energy-deposition-saves-time-and-costs/

Different AM Processes and relevant process physics

Properties	*Machining*	*Additive Manufacturing*	*Hybrid Manufacturing*
Shape Complexity	*Moderate*	*High*	*High*
Surface finish & Quality	*Moderate to High*	*Low*	*High*
Dimensional Accuracy	*High*	*Moderate*	*High*
Repeatability	*Moderate to High*	*Low*	*High*
Sustainability	*Low*	*High*	*High*
Multi-Material Use	*Rare*	*Frequent*	*Frequent*
Geometric Complexity	*Low to Moderate*	*High*	*High*
Design Versatility	*Limited*	*Flexible*	*Flexible*
Skill Requirement	*High*	*Moderate*	*High*
Mass Production	*Frequent*	*Rare*	*Rare*
Production Speed	*High*	*Low*	*Moderate*

Comparison between Machining, AM & Hybrid Manufacturing

Rapid Prototyping

- Rapid prototyping is the fast fabrication of a physical part, model, or assembly using 3D computer-aided design (CAD). The creation of the part, model, or assembly is usually completed using additive manufacturing, more commonly known as 3D printing.
- It includes a variety of manufacturing technologies, although most utilize layered additive manufacturing. However, other technologies used for RP include high-speed machining, casting, molding, and extruding.
- While additive manufacturing is the most common rapid prototyping process, other more conventional methods can also be used to create prototypes. These processes include:

- ❑ Subtractive: is a block of material carved to produce the desired shape using milling, grinding, or turning.
- ❑ Compressive: a semi-solid or liquid material is forced into the desired shape before solidified, such as casting, compressive sintering, or molding.

Rapid Tooling

Rapid tooling is known by many names, including prototype tooling and soft tooling, but it is essentially pared-back injection mold tooling enabling you to quickly and cheaply get parts. It is essential to differentiate between the concept and the realization as many ways of achieving the same results.

Conceptually, any injection mold tooling is manufactured quickly and inexpensively to enable testing and validation of parts before you invest in production tooling.

People manufacture rapid tooling mainly for testing and validation parts in the prototyping stages of new product development. Although other prototyping options such as 3D printing, CNC, or vacuum casting would generally allow faster and cheaper prototypes, the main advantage of rapid tooling lies in the process and materials.

References

- ***The 3D Printing Handbook, by Ben Redwood, Brian Garret, and Filemon Schöffer.***