Polymer Additive Manufacturing Technical Brief

Devin Young

Introduction:

Additive manufacturing (AM), colloquially known as 3D printing, is a disruptive technology whose influence is becoming more and more prevalent as the associated technologies progress. While AM has most often been used for rapid production of prototypes, AM is shifting toward the production of end-use, multifunctional components for a wide variety of applications.

Most AM processes follow a basic production process of thin layers of material being built one atop another to produce a component or part. The additive deposition of layers makes it possible to design AM parts with a variety of complexities that are non-trivial to create in other manufacturing methods. These complexities include geometry, multi-scale hierarchy, built-in functionality, and material selection. Taking advantage of AM complexities offers users an avenue for solving a myriad of problems in unique and novel ways.

The purpose of this brief is to provide an overview of AM technologies that use polymers as the primary building material. A brief history of polymer AM will be presented along with descriptions of common polymer AM technology types.

History of Polymer Additive Manufacturing:

The history of polymer additive manufacturing (AM) can be said to have begun with the patenting of stereolithography (SLA) in 1984 by Charles Hull. Dr. Hull found that he could create a solid 3D structure by curing consecutive layers of photopolymer one atop another.

Other processes for producing 3D structures would be developed over the coming decades. While the end result of each process was the same, a 3D structure, the fabrication method varied. As mentioned, SLA cures photopolymer liquid in layers to produce a part. Material printing methods (binder jetting and material jetting) use inkjet print heads to produce parts. Extrusion based methods melt a thermoplastic feedstock and extrude the molten material as thin layers to build a part. Powder bed fusion uses a laser or electron beam to melt or sinter plastic powder. Each method has strengths and weaknesses and is often selected with consideration of its idiosyncrasies.

Polymer AM proved a method for quickly producing prototype parts. This use became so prevalent that polymer AM is alternatively referred to as rapid prototyping. For many years, polymer AM technologies were limited to academia and proprietary industry uses. That began to change as patents began to expire and AM technologies became widely available. Now, an AM printer can be purchased cheaply. AM technologies have offered a vision of the future in which any object can be created from only a computer model. While that dream is still far off, polymer AM methods have been used to solve many problems beyond prototyping. With further research, polymer AM technologies will be able to further reduce manufacturing barriers for end-use, multifunctional components.

Description of the AM workflow:

Regardless of which AM process under consideration, they all possess a similar workflow of moving from design to finished part. The process begins with a computer model of the object to be fabricated. The model is usually created in a typical CAD program such as AutoCAD or SolidWorks.

The model is then imported into specialized "slicing" software that tessellates the model and divides it into slices stacked along a chosen build direction. A toolpath is generated for each slice which will be converted to layers in the actual part. Toolpaths for each layer are then exported into a numerical control code file, e.g. gcode. The numerical control code can then be loaded into the controller of an AM machine. The controller then reads the code and directs the machine to follow the toolpath, fabricating the part layer by layer until the part is completed. Fig. 1 shows the progression of the AM process from CAD model to numerical code to finished part.

While the details of each polymer AM method are different, the previously described process provides a general overview of the AM process.

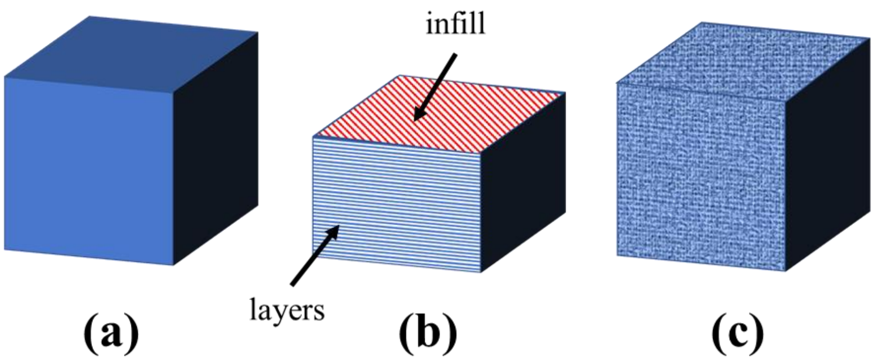

Fig. 1: AM workflow. The AM process begins with a CAD model of the part (a). Slicing software divides the part into layers and determines a toolpath to fill the inside of the part creating numerical control code (b). The numerical control code is loaded into an AM machine, and a part is produced (c).

Stereolithography:

Method summary: Liquid photopolymer resin is cured using a light source (e.g. UV, laser, electron beam). The light source traces a pattern in a vat of photopolymer resin to create a layer. Subsequent layers are built one atop another to form a part.

Pros:

- Quick fabrication time
- High resolution

Cons:

- Complex photopolymer resin chemistry
- Resin can prove messy
- Higher costs

Method description:

As previously mentioned, SLA is considered the first viable additive manufacturing technology. The most common form of SLA uses a vat of photopolymer and a light source to cure the material. The light source is most often UV, but other sources are available such as laser and electron beam.

The SLA process typically begins with a build platform barely submerged in a vat of photopolymer. A light source traces a pattern on the surface of the vat corresponding to the toolpath created by the slicing software. As one layer is completed, the build platform drops into the vat by the amount of a single layer height so the next layer can be cured. This process is repeated until the part has been completely formed.

Various configurations of vat polymerization have been developed, but most common are vector scanning and mask projection (Fig. 2). Vector scanning consists of a single light source tracing out the toolpath for each layer. This is the most common SLA method due to being relatively simple and inexpensive. Mask projection projects the pattern of an entire layer onto the liquid polymer and thus cures an entire layer simultaneously. While faster than vector scanning, mask projection requires greater optical capabilities to create the mask resulting in higher costs.

As an AM fabrication method, SLA has the benefit of rapid production and better resolution than other AM methods. To its detriment, SLA is often a more expensive process and the use of a liquid photopolymer resin makes the process messier than other technologies. Due to the need of a curing light source and adjustable optics, the cost of SLA is typically higher than other methods. Additionally, many of the base materials are prone to degradation over time, reducing the material properties of the part.

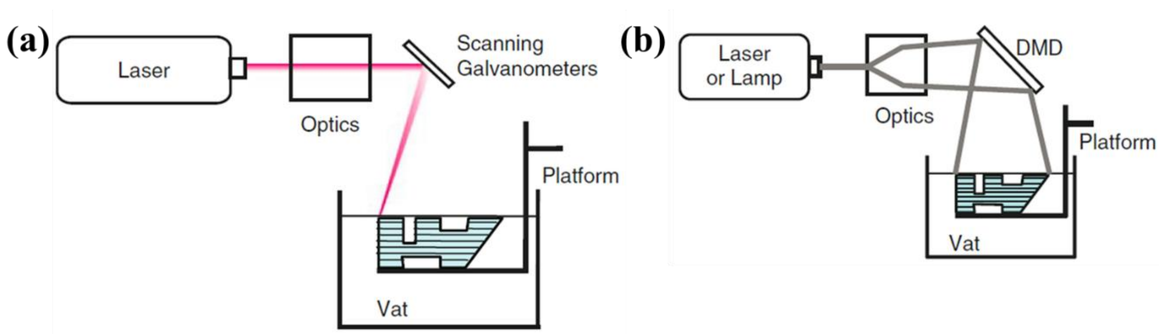

Fig. 2: Common SLA methods. (a) Vector scanning, where a single light source is used to trace out the part pattern. (b) Mask projection cures an entire layer simultaneously. [1]

Stereolithography systems:

- 3D systems
- Carbon
- Proto 3000
- Stratasys
- Formlabs

Video demonstration

Fused Filament Fabrication:

Method summary: Thermoplastic feedstock material is fed into an extrusion tool head. The feedstock is heated and extruded through a nozzle onto a build surface following the toolpath detailed in the numerical control code.

Pros:

- Simple and low cost
- Robust
- Wide material variety
- Multifunctionality

Cons:

- Slow fabrication speeds
- Inferior resolution compared to other methods

Method description:

Fused filament fabrication (FFF), often referred to by the trade name fused deposition modeling (FDM), is arguably the most common AM technology available today. This is largely due to the low cost and robustness of the fabrication method.

FFF is an extrusion based additive manufacturing method that most often uses thermoplastic materials to fabricate parts. A thermoplastic feedstock such as ABS or PLA is fed into an FFF printer as either pellets or filament. The feedstock material is raised significantly above its glass transition temperature until it is molten and can flow easily. The heated material is then extruded through a nozzle onto a build platform. Most FFF printers use a 3-axis gantry to move the toolhead, though more complex FFF printers have up to 6 axes. As each layer finishes extruding, either the toolhead is raised or the build platform lowered to begin the next layer. Fig. 3 provides a graphical representation of an FFF process.

Compared to other AM methods, FFF is a "clean" method since no powder or liquid polymer is involved. Besides being less messy, FFF allows users the opportunity to drop components or other devices into a part as it is being built, thus making FFF a good candidate for creating multifunctional parts. Researchers and manufacturers of FFF devices have also developed methods for adding reinforcement to FFF parts. This extends from the addition of short reinforcement fibers to feedstock materials to placement of continuous fiber tows. Some companies have been developing methods of directly printing glass and carbon fibers. Due to the aforementioned low cost and robustness of the technology, FFF stands as the best candidate for AM for space exploration purposes and has been shown to be a viable manufacturing method in microgravity.

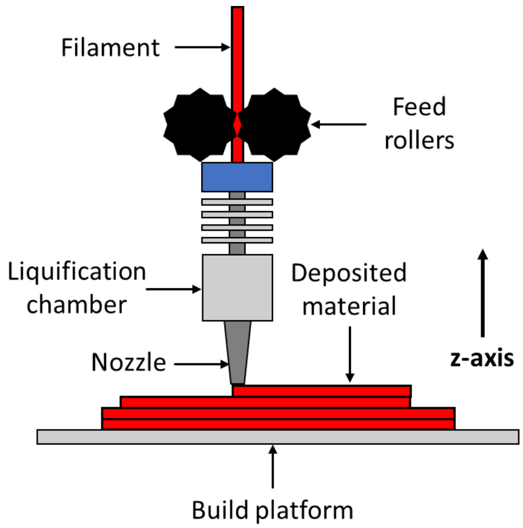

Fig. 3: Diagram of fused filament fabrication process.

Fused filament fabrication systems:

- Stratasys
- Lulzbot
- Markforged
- BigRep
- Continuous Composites

Video demonstration

Binder Jetting:

Method summary: Binder jetting uses inkjet printing technology to deposit a binder agent onto a polymer powder coated build platform. The resultant parts will have poor mechanical properties and low density, requiring additional processes for improvement in both areas.

Pros:

- Low cost (uses readily available and easily manufactured printing heads)
- Fast build speeds, print heads can be added to scale up production time
- Material and color variety
- No need for support structures

Cons:

- Post processing often required to densify part and increase mechanical performance
- Resultant part attributes are dependent upon powder properties

Method description:

A binder jetting process begins with a layer of plastic powder on a build platform. Inkjet printheads move over the build platform depositing a binding agent onto the powder according to a layer cross section. After a given layer is completed, a recoating process covers the first layer with new powder and more binding agent is deposited. Once the part has been fully printed, excess powder can be removed and recycled for future use. Fig. 4 provides a diagram of the binder jetting process.

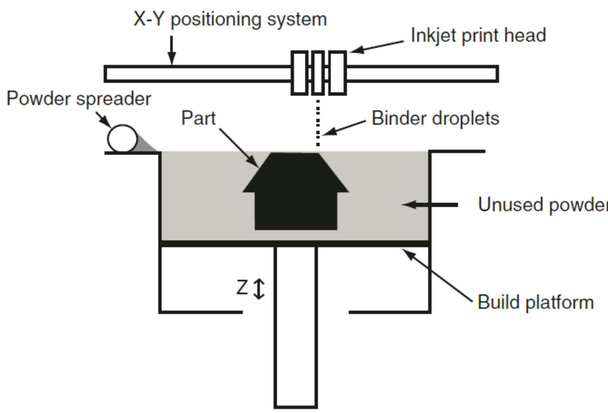

Fig. 4: Binder jetting setup. The unused powder serves as support material for the part [1].

Due to the presence of the binding agent, an as-built binder jetted part will have low density and poor mechanical performance. This is known as a green part which requires post processing to improve mechanical performance. Post processing may include sintering and part infiltration.

Since inkjet printheads are a relatively cheap technology, many printheads can be used in unison in a binder jetting application. In fact, an entire array of printheads may be lined up along the entire width of the print bed. This increases the fabrication speed significantly, but the savings in print time may be offset by time cost for post processing.

Binder jetting systems:

- ExOne
- Voxeljet

Video demonstration

Material Jetting:

Method summary: Material jetting uses inkjet printheads to directly print material onto a substrate. The printed material needs to be a liquid in order to be printed, so must either be something that can be quickly melted or a photopolymer resin which requires post-print curing.

Pros:

- Low cost (uses readily available and easily manufactured printing heads)
- Fast build speeds, print heads can be added to scale up production time
- Multi-color prints

Cons:

- Material choice is limited to photopolymers and waxes
- Poor part accuracy

Method description:

Material jetting is a direct deposition method using inkjet printheads. Polymer ink is jetted onto a build surface but must undergo a phase change of some kind to solidify. This can be done through a variety of methods, but photopolymerization using UV light is most common. Fig. 5 provides an example of material jetting.

Similar to binder jetting, inkjet printheads for material jetting can be scaled up to increase print speed. However, material jetting does not require the same amount of post processing needed for binder jetting. There are a number of printing challenges that must be addressed beforehand for any given build material. Among these issues are suspension of solid print particles, droplet formulation, proper droplet deposition, and conversion of liquid drops to solid drops. The interaction of these issues often proves detrimental to part fabrication and results in poor part accuracy.

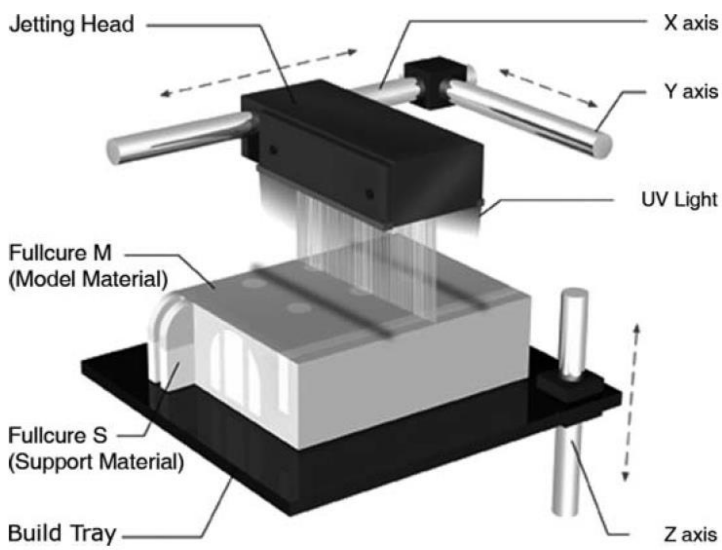

Fig. 5: Material jetting setup. Print heads can be lined up to cover the entire width of a build platform.

Material jetting systems:

- [Stratasys]
- [Solid Scape]
- [3D Systems]

[Video demonstration]

Powder Bed Fusion:

Method summary: Powder bed fusion (PBF) uses a laser, electron beam, or other heat source to selectively melt or sinter powdered plastic that has been spread on a build platform. After a layer has been fabricated, the build platform is dropped by a layer height, new powder material is applied, and the next layer is melted.

Pros:

- Powder serves as support structure
- Increased geometric complexity
- Small internal geometries

Cons:

- Reduced surface finish compared to other methods
- Needs pre-heating and/or cool-down time
- High monetary and energy costs

Method description:

In a PBF process, plastic powder is distributed evenly across a flat build surface. A heat source, often a laser or electron beam, traces out part cross sections on the surface of the powder. The powder is either melted or sintered together with surrounding particles. The powder often needs to be pre-heated before the material can be melted or sintered. Laser PBF systems typically have an IR heating lamp for powder heating. In an electron beam system, the beam can be defocused to quickly scan over the entire bed in order to heat the powder. This in part reduces the price of electron beam systems, but laser systems have higher resolution. Fig. 6 provides a diagram of a PBF process.

For polymer powders, a PBF part will not require support material for overhangs. The powder itself serves to support the part as it is being built. By taking advantage of this attribute, PBF has a greater amount of design flexibility when compared to other methods like FFF. PBF also requires careful consideration for powder application and handling. While the powder can be recycled after each build, the average particle size increases due to particles sintering or melting together near build lines. Furthermore, molecular weight of the powder can be altered due to being held at elevated temperatures. These changes can affect part quality with multiple uses of the same powder feedstock.

Powder bed fusion systems:

- Stratasys
- Prodways

Video demonstration

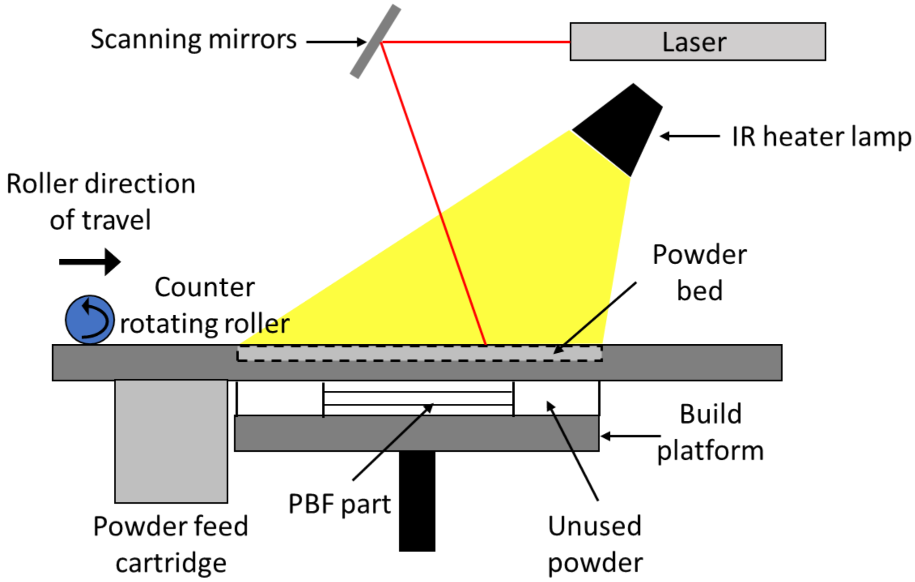

Fig. 6: Powder bed fusion process using a laser. The IR lamp can be omitted in an electron beam setup as the beam can be defocused and used to heat the powder bed.

Sources:

[1] Gibson, Ian, David W. Rosen, and Brent Stucker. "Additive Manufacturing Technologies: Rapid Prototyping to Direct Digital Manufacturing." Springer, 2010

Useful links

- https://3dprintingindustry.com/3d-printing-basics-free-beginners-guide#04-processes
- https://www.3printr.com/3d-printer-list/