Metal Additive Manufacturing Technical Brief

Devin Young

Introduction:

Additive manufacturing (AM), colloquially known as 3D printing, is a disruptive technology whose influence is becoming ever 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 produce 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 metals as the primary building material. The brief begins with a generalized description of AM workflow followed by descriptions of specific metal AM technologies.

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 determine how material will be deposited to build the 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 AM method vary, the workflow described here provides a general overview of the AM process.

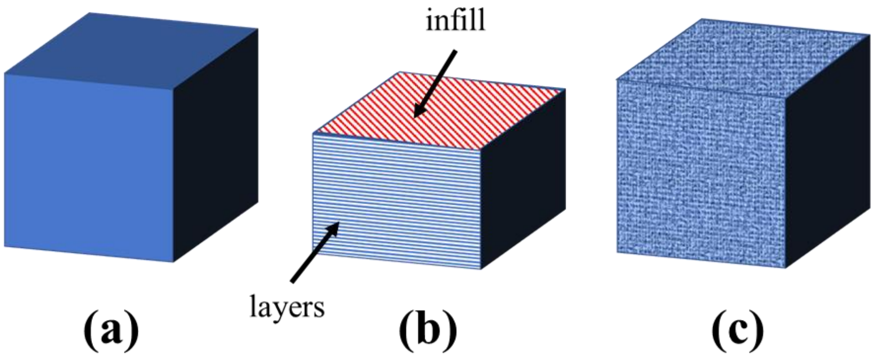

Fig. 1: AM workflow. The AM process begins with a CAD model of the part (a). Slicing software divides the part into layers and determines a toolpath to fill the inside of the part creating numerical control code (b). The numerical control code is loaded into an AM machine, and a part is produced (c).

Binder Jetting:

Method summary: Binder jetting uses inkjet printing technology to deposit a binder agent onto a metal 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 equipment costs
- Fast build speeds, print heads can be added to scale up production time

Cons:

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

Method description:

A binder jetting process begins with a layer of metal 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. 2 provides a diagram of the binder jetting process.

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 and 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 post processing.

Binder jetting systems:

- ExOne
- Xjet
- Desktop Metal
- Markforged

Video demonstration

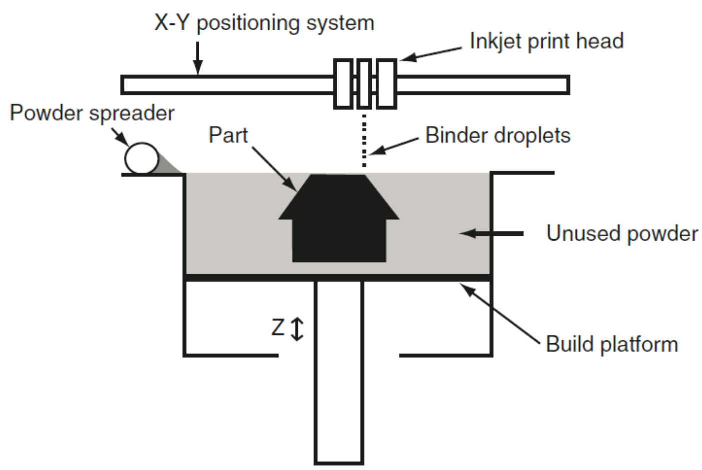

Fig. 2: Binder jetting setup. The unused powder serves as support material for the part [1].

Powder Bed Fusion:

Method summary: Powder bed fusion (PBF) uses a laser, electron beam, or other heat source to selectively melt or sinter powdered metal 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:

- Increased geometric complexity
- Small internal geometries

Cons:

- Poor surface finish
- Needs pre-heating and/or cool-down time
- High monetary, time, and energy costs

Method description:

In a PBF process, metal 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 is pre-heated to a temperature near the melting point 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. Fig. 3 provides a diagram of a PBF process.

Metal PBF parts will be required to be connected to a metal substrate to prevent warping in the part during the build. Unlike polymer PBF parts, the excess powder is not sufficient to support many features, and support structures will need to be added requiring additional post processing to remove.

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:

- 3Diligent
- 3D Systems
- Renishaw

Video demonstration

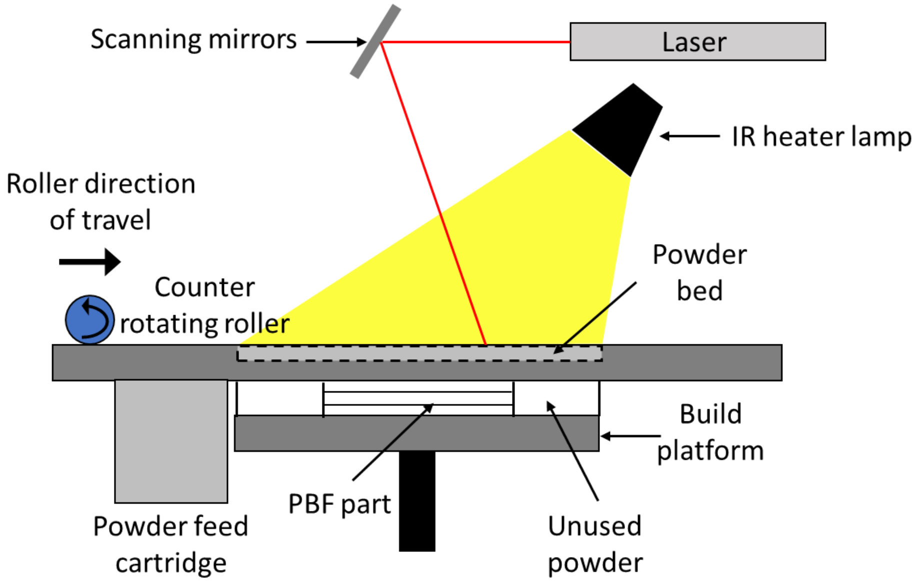

Fig. 3: Powder bed fusion process using a laser. The IR lamp can be omitted in an electron beam setup as the beam can be defocused and used to heat the powder bed.

Directed Energy Deposition:

Method summary: Directed energy deposition (DED) melts metal material as it is deposited onto a substrate. A nozzle directs metal powder or metal wire toward a given spot where a beam source (laser, electron beam, or plasma arc) melts the powder.

Pros:

- Metal powder only added where it is needed
- Non-vertical printing without support structures
- Can be performed on non-flat substrates, useful for repairs
- Control of microstructure
- Directionally solidified and single crystal structures

Cons:

- Poor resolution and surface finish
- Slow build speeds
- Less geometric complexity than PBF

Method description:

In directed energy deposition, either a powder or wire feedstock is fed into an energy source to melt the material as it makes contact with the build surface. A DED tool head may be constructed such that a heat source (e.g. laser, electron beam, or plasma arc) is directed toward a focal point that intersects the build surface. This generates a melt pool into which metal powder or wire is fed. The new material is melted, increasing the height of the melt pool to produce a new line of material. The melt pool quickly cools after the heat source is removed, solidifying the material in place. Fig. 4 provides a graphic showing a typical DED process.

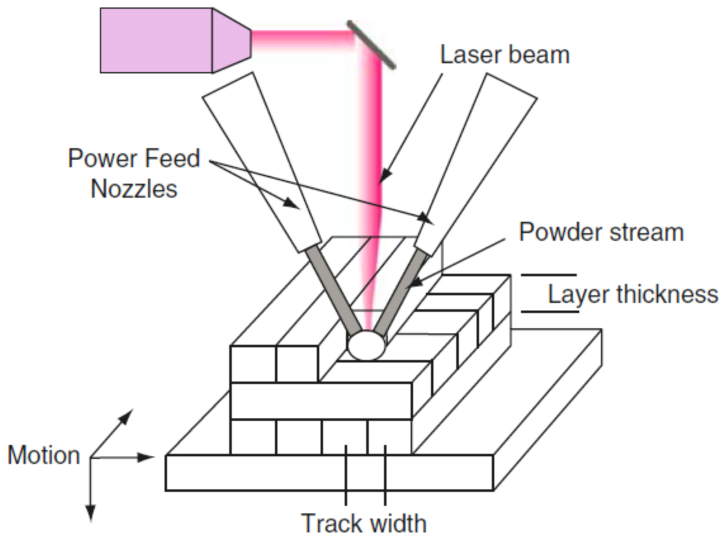

Figure 4: Directed energy deposition using a laser heat source.

Depending on the substrate size and weight, either the tool head or substrate is moved during printing. Heavier substrates are often kept stationary while the tool head moves. The opposite is often the case for lighter substrates. Powder feedstocks are accelerated to a sufficient velocity that gravity has little effect on the incoming particles as they move toward the melt pool. This allows DED to be performed at many different orientations. The combination of flexibility in material deposition orientation with the rapid melting and cooling of new material allows DED to be performed on non-flat substrates. This allows DED to be used to repair damaged metal parts. In fact, new material can be added to replace entire portions of broken parts.

Resolution and surface finish are often poor for DED processes. These can be refined with smaller melt pool sizes, but that increases the resultant build time. A balance must be struck between build time and resolution. As such, most DED parts will require some post processing to achieve the proper dimensionality.

Directed energy deposition systems:

- BeAM
- Sciaky
- Optomec

Video demonstration

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/
- https://www.3dhubs.com/knowledge-base/additive-manufacturing-process