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Metal additive manufacturing

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INDEX

1. METAL ADDITIVE MANUFACTURING

Metal additive manufacturing (MAM), also known as metal 3D printing, is the process of making three-dimensional, solid objects of nearly any shape or design layer by layer from digital 3D models.

The ability to create 3D objects of virtually any shape is what sets additive manufacturing apart from subtractive manufacturing, in which an object is created by cutting away at a solid block of material until the final product is complete.

In fact, compared to traditional manufacturing methods, the most significant advantage of AM is its freeform fabrication capability of complex parts directly from feedstock materials without involving traditional manufacturing methods such as extrusion, forging, casting and secondary machining processes to achieve desired shapes. The near net shaping capability makes AM a cost-effective technique due to its waste minimization. For example, the “buy-to-fly” ratio (the mass ratio between the raw material used to produce a component and the mass of the component) is 12–25:1 for aircraft titanium products made by traditional manufacturing methods, while it drops to 3–12:1 for a typical titanium component manufactured by AM processes. Furthermore, AM has high flexibility on feedstock material types, and unconsumed powders can be reused, making it more cost-efficient.

Metal additive manufacturing is a process that uses fine, metal powders to create strong, complex components that are designed either by using a computer-aided design (CAD) program or by taking a 3D scan of the object. First, a computer software slices the design into many layers that act as the framework for the additive manufacturing machine to follow. Then, once the design and framework are generated, they're sent to the machine to begin printing, though the exact printing process will vary depending on the machine being used.

A component produced using MAM may need post-processing due to requirements of the completed part. Post-processing can be costly and time-consuming if the finishing requirements are exceedingly strict. Typically, dimensional tolerances, surface roughness, and mechanical proprieties are some examples of factors that have an impact on the functionality of a component and may take time when post-processing the final product.

There are many types of metal additive manufacturing processes, and each comes with its own advantages and disadvantages.

Common types of metal additive manufacturing, as shown in Fig. 1, include:

- Powder bed fusion.
- Directed energy deposition.
- Binder jetting.
- Sheet lamination.

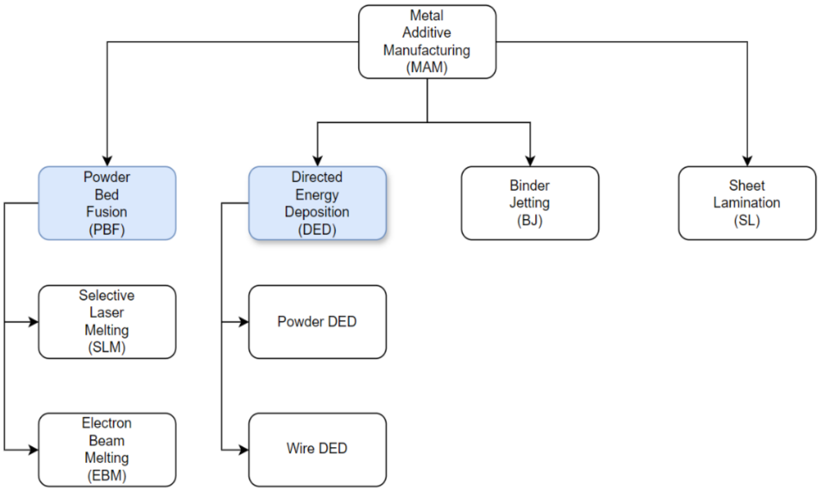


Fig. 1. Classification of Metal Additive Manufacturing processes

2. POWDER BED FUSION

The powder bed fusion process typically includes several printing techniques, such as electron beam melting (EBM) and selective laser melting (SLM). EBM excels in producing components with lower residual stresses, reducing the need for post-processing, while SLM presents an increased potential to produce comparatively smaller components with complex geometries.

Powder bed fusion uses lasers or electron beams to melt and fuse different powder materials into finished parts (Fig. 2).

Fig. 2. An example of powder bed fusion process

Here is a simplified, step-by-step look at the powder bed fusion process:

1. A layer of the chosen material is spread over the platform.
2. A laser or electron beam fuses the first layer or cross-section of the model.
3. A new layer of material is spread across the previous layer using a roller.
4. Further layers are fused.
5. The process repeats until the entire model is created. Loose, unfused powder remains in position but is removed during post processing.

- Advantages:
    - Lower cost due to a drop in machine prices.
    - Minimum to no supports needed for prints.
    - Unused powdered metal can be recycled.
    - Wide range of materials to choose from.
    - Powder acts as an integrated support structure.

- Disadvantages:

    - Relatively slow speed = longer print times.
    - Surface texture is similar to components created with sand casting or die casting.
    - Post-processing steps add time and increase cost.
    - Thermal distortion can cause the warping and shrinking of components.

Powder bed fusion can be divided into several branches, including Selective Laser Melting (SLM) and electron beam melting (EBM).

2.1 Selective laser melting (SLM)

The most commonly used form of powder bed fusion. The process usually requires a metal powder feedstock in the 15–45 µm range, which is spread in a thin layer with a roller. A laser is then projected towards the powder bed, where it melts the metal powder (Fig. 3).

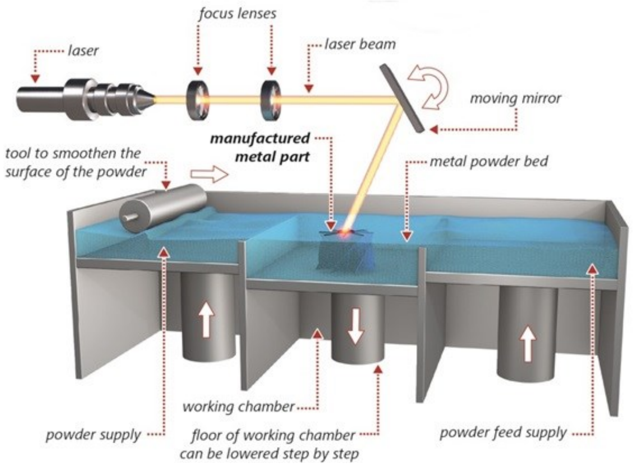


Fig. 3. Schematic representation of SLM system. All components are illustrated with arrows indicating a possible process dynamic.

The process occurs in an inert atmosphere which is either argon or nitrogen filled. Typical metals processed via SLM are stainless steel, aluminum, titanium, nickel-base alloys, and cobalt chrome alloys.

The need for an inert atmosphere means that there is a need for a closed build chamber.

After the print is complete, a trained operator removes it from the powder bed, cuts it away from the build plate, and begins post-processing.

2.2 Electron beam melting (EBM)

In this process, an electron beam is used as the thermal source rather than a laser (Fig. 4). This process operates within a vacuum environment to prevent oxidation and operates at high build chamber temperatures.

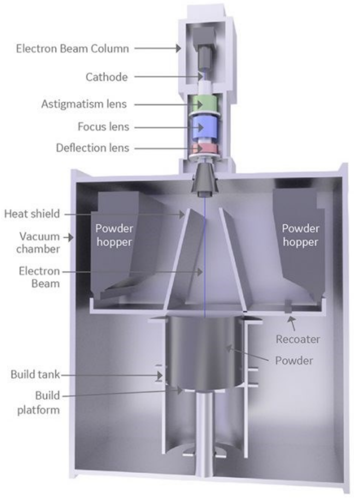


Fig. 4. Schematic representation of main components of EBM system.

Due to the higher energy density of an electron beam, a larger powder size distribution can be used (i.e. 50–120 µm). As a result of the larger powder size and therefore increased layer height, this process is typically quicker than the SLM process.

Alloys processed are similar to those used in SLM, with the exception that aluminum and other low boiling point metals tend to be vaporized when exposed to an electron beam.

EBM is safer than SLM for the working staff because it uses a larger powder size grain and that means it can cause less problems to the respiratory system, although security protocols and systems are widely used.

2.3 Process parameters

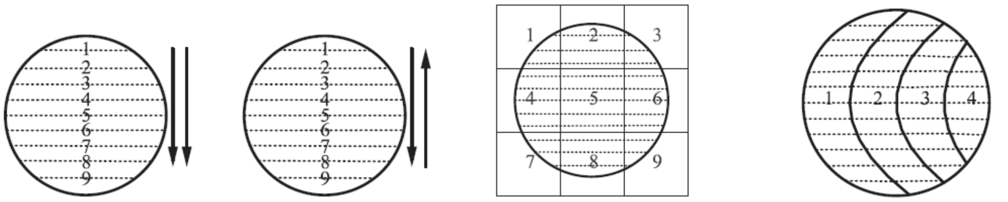
- Laser Power (or Electron Beam Power): The power of the laser beam or electron beam used to melt the powdered material.
- Scan Speed: The speed at which the laser beam or electron beam moves across the powder bed during the melting process.
- Layer Thickness: The thickness of each deposited layer of powdered material.
- Hatch Spacing (or Scan Line Spacing): The distance between adjacent laser scan lines or electron beam passes within each layer.
- Laser (or Electron Beam) Spot Size: The diameter of the laser beam or electron beam spot focused onto the powder bed.
- Powder Bed Temperature: The temperature of the powder bed during the printing process.
- Preheating Temperature: Preheating temperatures help reduce thermal gradients and improve adhesion between layers.
- Gas atmosphere: Shielding gas is required to prevent oxidation and evaporation phenomena of the molten pool and heat affected zone. Further benefits can be realized from the shielding gas as it will improve energy coupling between the laser and the material, blowing away the plasma that is formed above the surface.

Another important process parameter which nowadays a lot of groups of researchers are studying is the scan strategy. The electron beam scans the powder bed from the first filling line to the last filling line and subsequently jumps to the first filling line to repeat the scan process. Thus, there is an inevitable jump of the electron beam between two continuous scans, which may possibly cause powder pushed-away phenomena.

In addition, when forming a large part, a more consistent temperature in the formation zone is necessary to decrease thermal stress, which can reduce the distortion of substrate and improve the surface quality. Therefore, the scan strategy is essential for both powder pushed away phenomena and uneven temperature field.

When the electron beam jumps in the scan process, powder pushed-away phenomena easily occurs. Therefore, the electron beam jumps should be reduced in the scan strategy as many as possible.

There are many scan strategies which nowadays are studied, in particular: reverse scan mode, interlaced reverse scan mode, randomized block scan mode, and constant length scan mode, shown in Fig. 5.



(a) Iterative scan mode (b) Reverse scan mode (c) Randomized block scan mode (d) Constant length scan mode

Fig.5. Different types of scan strategies

In the reverse scan mode, Fig. 5b, the electron beam scans from filling line 1 to line 9; and then from filling line 9 to line 1 reversely; repeating the process until the metal powder is melted totally. This kind of scan mode can reduce electron beam jumps effectively and subsequently lower the possibility of powder pushed-away phenomena. It also makes the temperature field more homogeneous since the scan of even times and that of odd times are reversing. Reverse scan mode can effectively reduce the electron beam jumps in the formation zone. However, it also has disadvantages. To realize reverse scan mode, the positive scan data and reverse scan data on the same cross-section are needed in two different programmable machine controller documents stored in the programmable multi-axis controller. Nevertheless, the memory is limited and can just store one document. Thus, the scan process must be stopped to change the document between positive scan and reverse scan, which not only reduces the efficiency of forming greatly, but also has negative influence on the temperature field. The positive scan data and reverse scan data can be stored in one document, which is technically easily achieved, but when the three-dimensional model is large and has a complex shape, the scan data overflows storage space easily. Considering the problems mentioned above, interlaced reverse scan mode is designed. The positive scan data only collects odd-numbered filling lines, reverse scan data only collects even-numbered filling lines, which are stored in one document. In the positive scan, the electron beam just scans the odd-numbered filling lines (lines 1, 3, 5, 7, and 9 in Fig. 5b); in the reverse scan, the electron beam scans the even-numbered filling lines (lines 8, 6, 4, and 2 in Fig. 5b). This kind of scan mode not only reduces the electron beam jumps in the formation zone, but also eliminates the data redundancy and data switch in the forming process.

Randomized block scan mode first divides the cross-section into several small square blocks of equal size; then the electron beam scans the square blocks in accordance with the random order, shown in Fig. 5c. This kind of scan mode can improve the temperature field uniformity effectively. However, it has a negative influence on the powder pushed-away phenomena because of the random jumps of the electron beam.

Constant length scan mode is used to obtain a more consistent temperature field, it is better to adjust the energy input of filling line according to the length of the filling line. Hence, the process parameters should be different among the filling lines with different length. In fact, it is impossible to explore the different parameters for the filling line with different length. Figure 5d shows the constant length scan mode. The long filling line is divided into several lines with the constant length. Then, cross-section is divided into several regions with the constant-length filling line. If the optimum parameters of the constant-length filling line are fixed, the energy required by almost every kind of cross-sections can be ensured. This kind of scan mode not only simplifies the process parameters greatly, but also is conducive to improve the integrated performance of formed parts.

2.4 Ti6Al4V alloys powder bed fusion

Titanium alloy Ti6Al4V, also known as Grade 5 titanium, is one of the most used titanium alloys in powder bed fusion additive manufacturing processes. Ti6Al4V is a titanium alloy composed of approximately 90% titanium, 6% aluminum, and 4% vanadium, with small amounts of other elements. It offers an excellent combination of high strength, low density, corrosion resistance and biocompatibility (Fig.6).

Fig. 6. An example of a component in Ti6Al4V made with a PBF process.

Additive manufacturing processes of Ti alloys are still quite limited in industries as the traditional methods remain the preferred mechanism thanks to their already developed applications, high production rate and cheaper manufacturing cost at large quantities. The applications of AM-fabricated Ti alloys are limited to industries that favor customized parts with high-precision demands.

There are in fact many advantages of Ti6Al4V alloys that make it great for various applications in different industries, such as:

1. Aerospace and automotive industries because it has a high strength-to-weight ratio.
2. Medical applications (implants and prostheses). Titanium and its alloys are used in biomedical implants due to their excellent biological performance,

such as biocompatibility (non-toxic and low allergenic properties) and osseointegration. Demands for orthopedic implants (artificial knees, hip joints, elbows, bone plates, and screws for fracture fixation) as well as dental implants (removable prostheses, maxillofacial prostheses, and supporting materials) are increasing.

With the current development pace and greater availability of AM machines, additive manufacturing of Ti alloys is expected to expand greatly into other fields such as home appliances.

The most significant process parameters concerning Ti6Al4V alloys manufactured with powder bed fusion are:

- Laser Power (or Electron Beam Power): Laser or electron beam power typically vary depending on factors such as the desired melt pool size, scan speed, and layer thickness.
  Optimal laser powers for Ti6Al4V PBF range from 100 to 500 watts.
- Scan Speed: Scan speed influences the dwell time of the laser on each spot and directly affects the energy input into the material. It is adjusted to achieve the desired melt pool size and part quality.
  For Ti6Al4V PBF, scan speeds typically range from 300 to 1000 mm/s for SLM and up to over 1000 mm/s for EBM, although specific values may vary based on machine capabilities and material properties.
- Layer Thickness: Layer thickness is chosen based on the desired resolution, surface finish, and mechanical properties of the printed part. Thinner layers result in finer features but increase build time.
  Typical values for layer thickness in EB-PBF processes are 50 and 70µm, above the 20 – 50µm range of L-PBF processes.
- Hatch Spacing: Hatch spacing is adjusted to optimize part density and mechanical properties. It influences the amount of overlap between adjacent scan lines and affects part quality.
  For Ti6Al4V PBF, hatch spacing is typically set between 22.5–105 µm, ensuring sufficient overlap for good inter-layer bonding.

- Laser (or Electron Beam) Spot Size: Focus spot size is different, typically ~80 µm in diameter for SLM and ~100 µm in diameter for EBM.
- Preheating Temperature: For Ti6Al4V PBF, preheating temperatures are typically performed at each newly deposited layer, heating the material to around 60% of its melting point to sinter the feedstock powder particles.
- Powder Bed Temperature: Powder bed temperature is carefully controlled to ensure optimal part quality. It may vary based on the specific requirements of the material and process.

  For Ti6Al4V, powder bed temperatures are typically in the range of 400°C–800°C.
- Gas Atmosphere: Inert gas atmospheres, such as argon or nitrogen, are commonly used during Ti6Al4V LPBF. Studies have shown that the addiction of small amounts of oxygen and nitrogen to titanium alloys has been shown to increase its strength significantly. EBM processes use a vacuum atmosphere.

3. DIRECTED ENERGY DEPOSITION

Directed energy deposition, or DED, is a process typically used to repair or add onto an existing component. It spans several different manufacturing processes and typically costs more than other additive manufacturing types.
Advantage of DED over PBF and conventional methods is that reparation and reconfiguration is possible for DED processes.

Adding extra features on existing parts can offer the most cost-effective option while remanufacturing parts with new builds using PBF or conventional methods would be required to start again from the beginning.

Fig. 7. An example of DED process.

A typical DED machine consists of a nozzle mounted on a multi axis arm, which deposits melted material onto the specified surface, where it solidifies (Fig. 7).

The nozzle can move in multiple directions and is not fixed to a specific axis.

The material, which can be deposited from any angle due to 4 and 5 axis machines, is melted upon deposition with a focused thermal energy, such as a laser beam, electron beam, or plasma arc. Using information from the CAD file, the CNC head and/or bed are moved along the build path, creating the final component.

Here’s a simplified look at the directed energy deposition process:

1. An arm with 4-5 axis points moves a nozzle around a fixed object.
2. Material is pushed through the nozzle and added onto existing substrates.
3. Material is either provided in wire or powder form.
4. The added material is melted using an electron beam, laser, or plasma arc upon deposition.
5. More material is added layer by layer as needed, creating or repairing new material features on the existing object.

The process can be used with polymers, ceramics but is typically used with metals, in the form of either powder or wire.

Advantages:

- Faster build rate than other metal AM technologies.
- Creates dense and strong parts.
- Less material waste.
- Larger components - Some machines can build parts up to several meters high.
- Compatible with a wide range of materials.

Disadvantages:

- Parts created with DED are lower in resolution and have a rougher surface finish than some other metal AM technologies.
- DED machines are comparably expensive to other metal additive manufacturing machines.
- Support structures can’t be used during the printing process, making features like overhangs unfeasible.

3.1 Powder and wire directed energy deposition

The DED process uses material in powder form (a) or in wire (b).

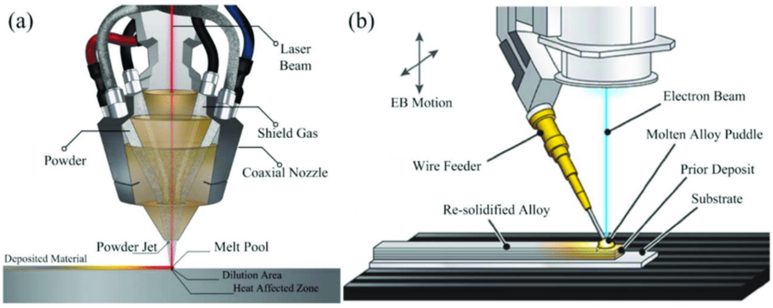


Fig. 7. Schematic representation of DED processes using material (a) in powder form or (b) in wire form.

Wire is less accurate due to the nature of a pre-formed shape but it is more material efficient when compared to powder as only required material is used.

Powder DED is similar to SLM, in that a laser and metal powder is used to create metal parts. Instead of spreading powder on the bed and melting it with a laser, powder DED machines blow powder out of a print head onto a part, using a laser to fuse it to the part in construction. The method of material melting varies between a laser, an electron beam or plasma arc, all within a controlled chamber where the atmosphere has reduced oxygen levels.

DED can be used for repairing parts and coatings and can adjust real-time powder compositions and fabricate products with site-specific compositions and properties.

Directed Energy Deposition can process a wide range of metal materials, including stainless steel, titanium, aluminum, nickel alloys, cobalt-chrome, and copper.

3.2 Process parameters

- Laser Power (or Electron Beam Power): The power of the laser beam or electron beam used to melt the metal feedstock material.
- Beam Diameter (or Spot Size): The diameter of the laser beam or electron beam spot focused onto the substrate surface.

- Hatch spacing: The distance between adjacent laser scan lines or electron beam passes within each layer.
- Scan Speed: The speed at which the laser beam or electron beam moves across the substrate surface during the deposition process.
- Layer Thickness: The thickness of each deposited layer of material.
- Gas Flow Rate and Composition: The flow rate and composition of the shielding gas (e.g., argon, nitrogen) used to protect the melt pool from oxidation and control the thermal environment.

Regarding the scan strategy for directed energy deposition there are two methods. The horizontal and vertical scanning strategies, that are illustrated in Fig. 8. In horizontal scanning, the scanning directions of two adjacent deposition tracks are opposite and both travel in the horizontal direction relative to the nozzle. After each layer deposition, the substrate travels down for a preset distance. The successive layers follow the same strategy. In vertical scanning, the substrate travels in a vertical direction relative to the nozzle.

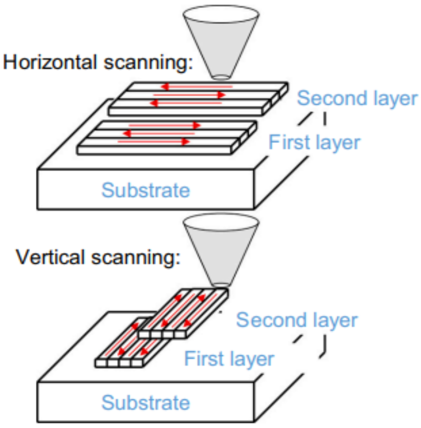


Fig. 8. Types of scan strategy

3.3 Ti6Al4V alloys directed energy deposition

The most significant process parameters concerning Ti6Al4V alloys manufactured with Directed Energy Deposition are:

- Laser Power (or Electron Beam Power): It directly affects the energy input into the system and influences factors such as melting depth, deposition rate, and heat-affected zone.
  DED typical laser power ranges from 500 W to a few kW.
- Beam Diameter (or Spot Size): It determines the spatial resolution of the deposition process and affects the size and shape of the deposited tracks.
  DED typical laser spots sizes ranges from 1 to 10 mm.
- Hatch spacing: Insufficient hatch spacing may result in the formation of internal pores and cracks, while excessive hatch spacing can cause a non-uniform molten pool, leading to reduced productivity and high internal stresses. Hatch spacing values depend on spot size and could vary.
- Scan Speed: It affects the heating and cooling rates, as well as the size and shape of the deposited tracks.
  DED exhibits a much higher deposition rate than PBF.
- Layer Thickness: It determines the resolution and surface finish of the printed part and can be adjusted to optimize build time and part quality.
  Typical layer thicknesses of 200-1000 μm.
- Gas Flow Rate and Composition: It influences the quality of the deposited material and the formation of defects such as porosity.

4. BINDER JETTING

The binder jetting process only uses two materials: a binder and a powder-based material (typically metal).

The binder (usually a liquid) serves as a bonding agent between the layers of powder.

A print head moves horizontally, depositing layers on the build platform and binding the material (Fig. 9). After each layer, the object being printed is lowered on its build platform.

Fig. 9. An example of binder jetting process.

Due to the method of binding, the material characteristics are not always suitable for structural parts and despite the relative speed of printing, additional post processing can add significant time to the overall process.

The object being printed is self-supported within the powder bed and is removed from the unbound powder once completed.

A heated build chamber can help to speed up the printing process by increasing the viscosity of the materials.

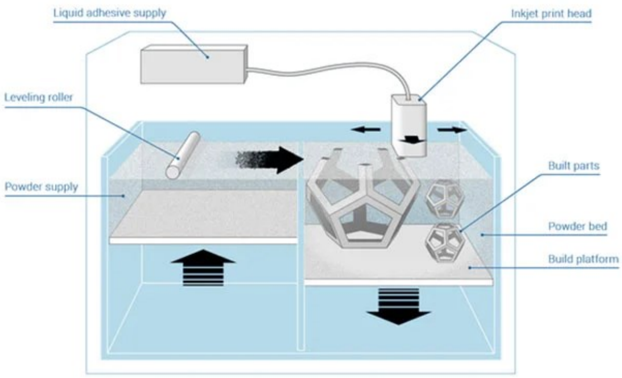


Fig. 10. Schematic representation of Binder Jetting system. All components are illustrated with arrows indicating a possible process dynamic.

A step-by-step look at the binder jetting process:

1. The powder material is spread across the build platform.
2. The print head layers the binder adhesive on top of the powder.
3. The build platform is lowered.
4. Another layer of powder is applied to the previous layer, resulting in an object being formed where the powder and liquid are bound.
5. The process repeats until the desired shape is finished. The excess unbonded metal powder surrounding the object is removed for re-use.

- Advantages:
    - Printing supports aren’t always needed, cutting down on waste and post-processing.
    - Can recycle up to 99% of loose powder.
    - Allows to produce complex designs without increasing costs.
    - Can produce multiple parts in one print, reducing costs and saving time.
    - Manufactured components are isotropic, meaning they’re equally strong in all directions.

- Disadvantages:
    - Binder jetting machines cost more than most subtractive manufacturing technologies.

Binder jetting can process a wide range of metal materials, such as: stainless steel, tool steel, bronze, inconel, titanium and cobalt chrome.

Despite several advantages of the binder jet 3D printing technology over other AM methods, the fabrication of parts with high-density, fine microstructure, and low pickup of impurities is still challenging.

The formation of large and interaggregate pores during binder jetting is demonstrated and discussed.

4.1 Process parameters

- Layer Thickness: The thickness of each deposited layer of powder material.
- Binder Deposition Rate: The rate at which the liquid binding agent is deposited onto the powder bed.
- Binder Drop Size: The size of individual binder droplets deposited onto the powder bed.
- Binder Penetration Depth: The depth to which the binder penetrates the powder bed. It affects the bonding between powder particles and influences part strength.
- Binder Saturation Level: The amount of binder absorbed by the powder material.
- Powder Bed Temperature: The temperature of the powder bed during the printing process.

4.2 Ti6Al4V alloys binder jetting

The most significant process parameters concerning Ti6Al4V alloys manufactured with Binder Jetting are:

- Layer Thickness: It influences the resolution, surface finish, and dimensional accuracy of the printed part. It is variable in the range of 30 to 90 µm depending on the printing aim.
- Binder Drop Frequency: It affects the bonding strength between powder particles and influences part density. Typical values registered are around 3000 Hz.
- Binder Drop Size: It influences the resolution, surface roughness, and dimensional accuracy of the printed part. Droplet volume could be in some specific cases around 25,9 pL.
- Binder Saturation Level: It affects the bonding strength and mechanical properties of the printed part. It is variable in the range of 40 to 60% depending on the printed parts.
- Powder Bed Temperature: It affects the flowability of the powder material. Bed temperature is generally variable in the range of 40 to 60°C.

5. SHEET LAMINATION

Sheet lamination is a particular process that does not use metal powder to create components. It includes two types of manufacturing: ultrasonic additive manufacturing (UAM) and laminated object manufacturing (LOM).

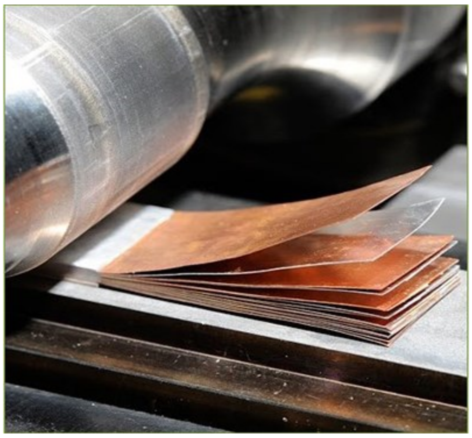


Fig. 11. A picture from a Sheet Lamination process.

UAM uses sheets of metal that are bound together using ultrasonic welding. LOM uses a similar layer-by-layer tactic but instead uses paper as the primary material and adhesive instead of metal and welding, respectively.

The ultrasonic additive manufacturing (UAM) process is as follows:

1. Thin metal sheets are placed.
2. Ultrasonic vibrations create a friction-like relative motion between two surfaces that are held together under pressure.
3. This action causes shearing and plastic deformation between asperities of the opposing surfaces, which disperses surface oxides and contaminants.
4. As the asperities collapse, metal-to-metal contact is increased creating solid-state bonding between the parts through heat and pressure.

UAM uses metals like aluminum, copper, stainless steel and titanium. The process is held at low temperature and allows for internal geometries to be created.

The process can bond different materials and requires relatively little energy, as the metal is not melted.

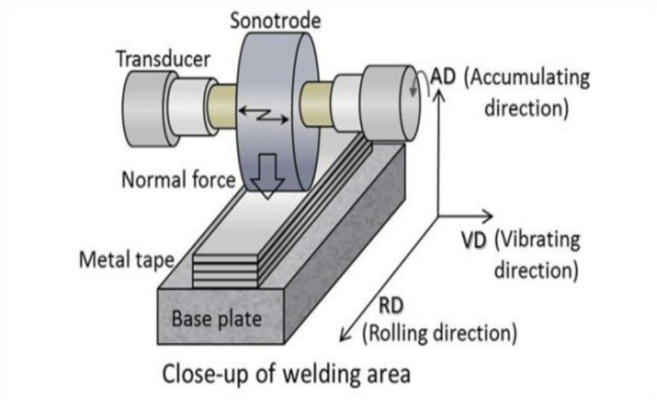


Fig. 12. Schematic representation of Ultrasonic Additive Manufacturing system. All components are illustrated with arrows indicating a possible process dynamic.

The process does require additional cnc machining and removal of the unbound metal, often during the welding process.

Advantages:

- Low cost, ease of material handling.
- Bonding multiple metals: UAM doesn’t use high heats that can change the microstructure of metals. Because of this, it can be used to bond dissimilar metals without creating mismatches.

Disadvantages:

- High costs of the equipment.

5.1 Process parameters

- Ultrasonic Power: The power level of the ultrasonic vibrations applied to the sonotrode (tool) during the welding process.
- Amplitude: It could normally range from 10 to 50 μm. It is the sonotrode longitudinal oscillatory displacement.
- Sonotrode Frequency: The frequency of the ultrasonic vibrations applied to the sonotrode.
- Normal Force: The force applied to the metal foils during the welding process.
- Welding Speed: The speed at which the sonotrode moves across the metal foils during the welding process. It affects the heat input, material flow, and overall build time, influencing part quality and dimensional accuracy.
- Foil Thickness: The thickness of the metal foils used in the UAM process.
- Tool Design and Geometry: The shape, size, and configuration of the sonotrode used for welding.
- Process Temperatures

5.2 Ti6Al4V alloys sheet lamination

The most significant process parameters concerning Ti6Al4V alloys manufactured with UAM are:

- Ultrasonic Power: It influences the bonding strength and material flow. Values of laser power could vary.
- Sonotrode Frequency: It determines the rate at which the metal foils are welded together. Typical value of ultrasonic frequency is 27 kHz.

- Normal Force: It is the downward force applied by the sonotrode onto the mating surfaces and can range from 100 N to 9000 N depending on the build materials. In the case of Ti6Al4V alloys a frequent value of static pressure is around 800 N.
- Foil Thickness: It affects the layer height and mechanical properties of the final part. Frequent values of layer thickness range between 25 μm and 40 μm.
- Tool Design and Geometry: The sonotrode comes into direct contact with the materials and provides the necessary energy for bonding. Sonotrodes are usually made of titanium, aluminum, or steel with varying surface finish intended for different applications.
- Process Temperatures: UAM operates at temperatures much lower than the melting temperatures of the starting materials, usually 0.3–0.5 Tm.

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