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Review Article

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A Review Paper on Understanding the Various Methods and Challenges of Metal 3D Printing

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Abstract

A component of additive manufacturing (AM), which has transformed the industrial sector by producing complex and specialized parts, is metal 3D printing. As it advances in future it is crucial to know and gain knowledge on understanding the various methods and challenges associated with metal 3D printing. This review paper aims to provide a brief review on the various methods used in metal 3D printing along with the challenges faced during the process. The many techniques include the Power Bed Fusion (PBF) process, which uses selective laser melting (SLM) and electron beam melting (EBM), in addition to Directed Energy depositing techniques, which use laser metal deposition (LMD) and electron beam freeform fabrication (EBFF). Furthermore, the paper addresses the challenges encountered during metal 3D printing from material selection to post-processing. This review provides valuable insights and knowledge to researchers, engineers and industry professionals with the knowledge and valuable insights to advance the field further. It enables the realization of its full potential in different industries including aerospace, automotive, and healthcare.

Keywords

Metal 3D printing, Power bed fusion, Electron beam freeform manufacturing, Selective laser melting, Electron beam melting

Introduction

A variety of sectors have adopted metal 3D printing, also known as AM, as a game-changing technology. It makes it possible to produce intricate and individualized metal parts with unprecedented design freedom. An overview of metal 3D printing methods, materials, applications, and difficulties is the goal of this literature review. The significant contributions of two leading authors in the field are highlighted. Ian Gibson is a well-known author and researcher in the area of AM. "Additive Manufacturing Technologies:" is the title of his book. 3D Printing, Fast Prototyping, and Direct Computerized assembling," Gibson et al. gives a complete outline of added substance producing innovations, including metal 3D printing. The book is an essential reference for researchers and practitioners because it covers the principles, processes, materials, and applications of metal 3D printing [1].

Yap et al. has made significant commitments to the comprehension and improvement of particular SLM innovations. "A review of selective laser melting:" is the title of his review article. materials and applications," Yap et al. talks about the functioning standards, process boundaries, and material contemplations for SLM. The article likewise features the uses of SLM in various businesses and gives experiences into the difficulties and future possibilities of the innovation [2]. This review provides a comprehensive understanding of metal 3D printing, including methods like SLM, EBM, and binder jetting, as well as the materials used and their properties, by synthesizing the works of these authors and other relevant literature. It also looks at the many different ways that metal 3D printing can be used in industries like aerospace, automotive, healthcare, and others. The challenges of metal 3D printing, such as part quality, post-processing, and cost, are also discussed in the review, paving the way for future innovations and advancements in the field.

Metal 3D printing is a process in which it creates 3D objects from a digital model by depositing material layer by layer. It reduces multiple part assembly into single part. By using topology optimization, it makes very light metal parts to high strength components [3]. Various metal 3D printing methods are PBF techniques in which it includes SLM an EBM and other techniques are Direct Energy Deposition (DED) techniques and binder jetting techniques which includes wire arc additive manufacturing (WAAM) and laser engineered net shaping in DED whereas in binder jetting techniques it comprises of metal binder jetting [4]. SLM uses a laser to melt thin layers of metal powder, which are then fused together to form a solid. SLM is a relatively precise and fast method, but it is expensive whereas direct metal laser sintering (DMLS) is similar to SLM, but in this process the laser is used to sinter, or heat the metal powder together, rather than melting it. This makes DMLS a slightly slower process than SLM, but it can produce parts with better surface finish and mechanical properties [5].

EBM uses an electron beam to melt thin layers of metal powder, which are then fused together by which it creates a solid part. EBM is a very precise method, but it is expensive and slow [6]. DED is a metal 3D printing technique that involves the precise deposition of metal powders or wires using a focused energy source, such as a laser or electron beam. This method offers advantages such as high deposition rates, scalability, and the ability to repair or add material to existing components. The binder jetting method uses a print head which deposits a binder material onto a bed of metal powder. Powder particles are held together by the binder material, and then the object is sintered to solidify it. Binder jetting is an inexpensive and relatively fast method, but it produces parts with lower accuracy and surface finish than other methods [7]. The challenges in metal 3D printing are, Porosity: It is a common defect in metal 3D printed parts that can occur due to incomplete melting of the metal powder or poor powder distribution. It weakens the mechanical properties of the printed part. Residual stress: This is another common defect in metal 3D printed parts that can occur due to the rapid heating and cooling of the metal during printing. Residual stress can lead to part deformation or cracking. Heat-affected zone (HAZ): The HAZ is the region of the substrate that is heated and affected by the laser or electron beam during DED printing. The HAZ can have different properties than the surrounding material, which leads to defects in the printed part. Material cost: The cost of metal powders for DED printing can be high. Process control: DED printing is a complex process that can be difficult to control, which can lead to defects in the printed part [8].

Classification of Metal 3D Printing Methods

PBF Techniques

SLM

In order to fabricate metal components from metallic powders, the AM, sometimes referred to as 3D printing, process known as SLM was first developed at the Fraunhofer Institute ILT in Aachen, Germany. A high-energy laser beam is used in a PBF technique to melt powder materials together and create 3D solid objects layer by layer [9, 10]. The computer-aided design (CAD) model, which represents the geometrical aspects of the part, is created as the first step in the SLM process. The 3D model is then fed into the SLM equipment after being cut into a stack of 2D layers using software like Magics. As illustrated in figure 1, a powder delivery system first applies a thin coating of powder material to a substrate before printing begins. The powder material is then fused together using the prescribed path from the loaded file after being scanned by a high-energy laser beam in a chosen location. An additional thin coating of powder is distributed on top of the previously processed layer once the scanning procedure is complete, and then the construction platform is lowered by one layer thickness. Laser scanning is then performed. The intended part can be constructed layer by layer by repeating the process for additional layers. For attaining a compromise between fine resolution and adequate powder flowability, the layer thickness typically varies from 20 to 100 m. To stop the oxidation of as-printed materials, the SLM process is often carried out in a chamber filled with argon or nitrogen. As indicated in figure 1, a few processing factors, such as laser power, scanning velocity, layer thickness, and hatch spacing, may be changed to optimize the SLM process.

SLM process

An Ytterbium fiber laser (YLR-500, IPG) with a maximum power of 500 W and a wavelength of 1070 nm was used for the SLM studies [10]. In order to prevent the combined powder from oxidizing, the laser beam size was increased to 200 m, and Argon was employed as the protective gas. To improve processing settings for the laser power (125 - 225 W with intervals of 25 W) and the scanning velocity (10 - 30 mm/s with intervals of 10 mm/s), preliminary single-track SLM tests were carried out. During multi-track tests, the overlapping ratio was set at 50%. The SLM tests with pure Ti powder without nano-SiC were conducted as a comparison [9, 11]. A Concept Laser M2 Cussing SLM (laser powder-bed)

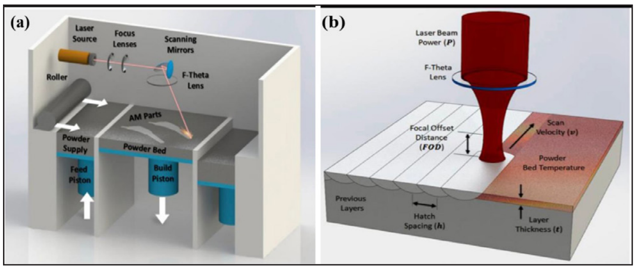

Figure 1: Schematic illustrations of **(a)** SLM machine and **(b)** processing parameters [5].

technology was used to create each specimen. The Yb-Fibre laser in the M2 system has a maximum power of 200 W, a maximum track width of 150 m, and a maximum scan speed of 7000 mm/s. A Z increment (vertical) of 30 m was used to construct each specimen. The entire procedure was done in an environment of argon with about 0.1% oxygen. To create the specimens, an "island scanning strategy" was used, in which the filled layer was split into numerous squares (islands), with each island being constructed constantly and randomly. The laser is separately raster-scanned inside each island. After carefully melting the islands, the layer's perimeter is scanned with a laser to smooth out the surface. These islands are moved in the X and Y axes by 1 mm for each additional layer. The island deposition approach seeks to balance the lingering tensions in the construction.

Parametric study of SLM

The initial step was to conduct single-track SLM tests to identify the best SLM processing settings for producing defect-free TMNCs. Our first research revealed that, under all processing settings, single-tracks with an excessive amount of nano-SiC (> 5 wt.%) can have serious cracking problems. Therefore, the range of nano-SiC addition 0 - 5 wt.% was deemed adequate for carrying out the parametric analysis and microstructural examination, as illustrated in figure 2. The cross-sectional morphologies of TMNCs with 5 wt.% nano-SiC processed by single-track SLM with varied laser strengths and scanning velocities are shown in figure 2 as an illustration of a parametric research. The findings demonstrate that the TMNCs display poor quality with a significant porosity and 0% dilution rate (into the substrate) for low laser energy input (Zone I). Relatively dense tracks with the right dilution rate may be produced with a modest laser energy input (Zone II). Additionally, an enlarged view (Figure 2) reveals that the synthetic TMNCs are made up of brilliant grains with dendritic or globular shape and dark grains that are equiaxed. On the contrary hand, if laser energy input (Zone III) is increased further, a structure with alternate bright and dark parts is formed along with a larger dilution rate (Figure 2). In this study, two sets of processing parameters—a moderate energy input of laser power 150 W and scanning velocity 20 mm/s and a high energy input of laser power 200 W and scanning velocity 20 mm/s—were chosen to examine the quality of TMNCs and the microstructural change as affected by laser energy input. By using an electron beam rather than a laser, EBM fuses together metal powder particles to create solid objects.

EBAM

An electron beam is used as the energy source in the sophisticated manufacturing process known as electron beam additive manufacturing (EBAM), which melts and fuses metal powders layer by layer to produce intricate three-dimensional structures. Until the portion is finished, the procedure is repeated.

In figure 2 shows the details of parts and its working [12, 13]. DMLS is a relatively fast process, and it can be used to fabricate parts quickly. These advantages make EBAM a promising technique for the production of complex and high-performance Ti-6Al-4V components in various industries, including aerospace, automotive, and medical applications.

In figure 3, a powder layer is rolled or scraped to a thickness of several mean powder particle diameters, and then a laser or electron beam powered by CAD is used to melt just the desired portions of the powder layer [11]. To print a 3D object, the layer of powder that has been selectively melted drops down (along the Z-axis) and a fresh layer of powder is made. While the selective EBM process is carried out in a vacuum, the SLM of the powder bed in figure 3 is carried out in an inert atmosphere using either pure nitrogen or argon. Although certain specialized system designs now permit producing big components in sizes approaching 1 m^3, both processes (SLM or EBM) are currently accomplished in commercial systems with slightly constrained build capacities of about 0.09 m^3.

Over the past two years, PBF (SLM and EBM) technologies have spread throughout the world, and commercial systems are being used more frequently in hospital 3D printing hubs or laboratories to meet the needs of orthopaedic and other medical departments for point-of-contact, patient-specific surgical devices [11]. The main characteristics of the PBF technologies while employing EBM are summarized. The electron cannon, beam generating system, and scanning system. The powder is gravity fed onto the powder bed by powder cassettes (3) where it is raked (r) into a new layer that is preheated by the scanning electron beam and then selectively melted in accordance with instructions from CAD software characterizing the layer building strategy required to construct the particular product. An optical (light) micrograph of a solid Ti-6Al-4V product made using the EBM process demonstrating the characteristic platelet microstructure in the phase. The Ti-6Al-4V solid materials produced by SLM fabrication have a lot of the same microstructural characteristics. The lower SLM powder bed

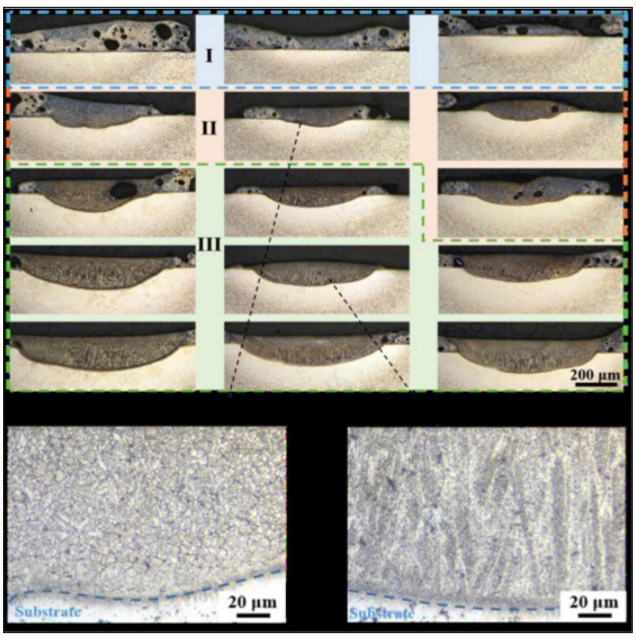

Figure 2: Studying the SLM of TMNCs with 5% nano-SiC parametrically. Cross-sectional OM pictures illustrating how laser power input and scanning speed impact morphology and microstructure. High magnitude OM pictures of TMNCs created at high and moderate laser energies, respectively [8].

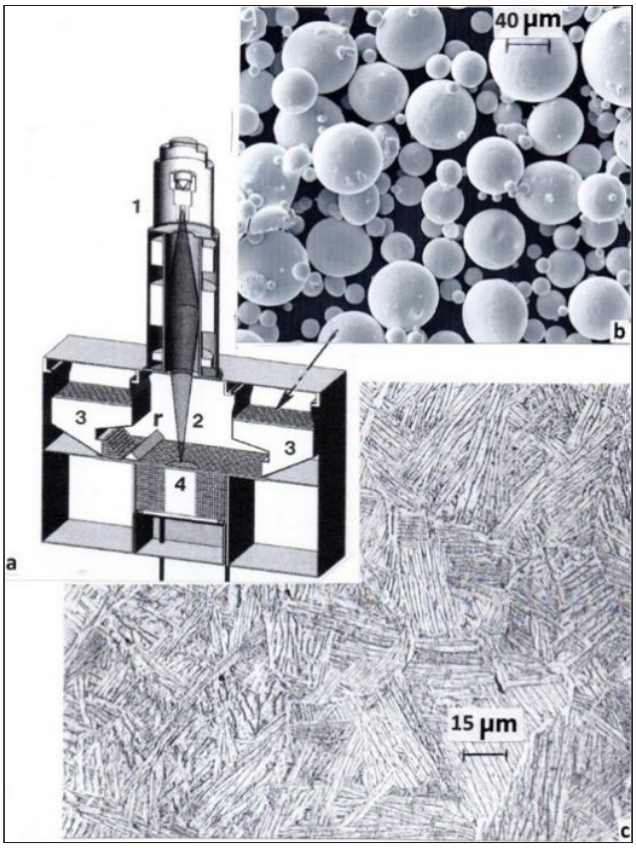

Figure 3: Representation of PBFAM.

temperatures and faster cooling or cooling rate are the primary differences between EBM and SLM manufactured metal or alloy products. Some SLM experience internal strain as a result, resulting in products that frequently need hot isostatic processing (HIPing) to remove the resulting internal strain as well as product warping or other deformities. Additionally, SLM product surfaces are frequently smoother, which might be a crucial characteristic for particular applications.

- Since 1998, the RP system has made it possible to build products in three weeks.
- SLM uses a variety of structural powders and polymers.
- The SLM method does not require support structures.
- EBM components are more expensive than SLM ones.
- Using a variety of metal powders with EBM is one way to produce high-quality metal components with no internal tensions.
- EBM may be used to create fully dense items with extremely homogenous microstructures. However, SLM only creates dense components and could result in homogenous microstructures.
- EBM has superior microstructural control than traditional techniques.
- DMLS can produce alloy components by fully melting metal particles.
- The aforementioned AM methods may easily produce complicated components.
- The PBF method decreases the supply of raw materials.
- The PBF technique may be used to create intricate and precise dimensional objects from a variety of material powders.
- By deciding on the necessary characteristics, desired mechanical PBF components may be obtained.
- Compared to 3D printing and fused deposition modeling, the SLM technique is more costly.
- EBM items are of higher quality than SLM metal components.
- EBM is pricey and needs vacuum operation.
- For EBM components, conventional secondary processes are required.
- When using powder materials, the cost of PBF equipment and supplies is considerable.

DED techniques

Laser metal deposition

An important metal AM technique, laser melting deposition (LMD) involves using a high-power laser to melt and fuse powdered material layers to create complex 3D metal structures (Figure 4). In this study, the researchers used a hybrid process that combines LMD and SLM with different types of titanium alloy plates. LMD parts geometric accuracy, microstructures, and mechanical properties are strongly influenced by the processing parameters that need to be optimized. In LMD components, mechanical strength and ductility are well-balanced. The tensile and fatigue characteristics of LMD Ti-6Al-4V components are significantly influenced by the microstructure that is created during the manufacturing process. LMD might be used in more commercial applications by regulating the processing parameters.

Mathematical frameworks that can describe the interactions among the laser beam and the deposited material still need to be developed. Mathematical frameworks that can describe the interactions among the laser beam and the deposited material still need to be developed.

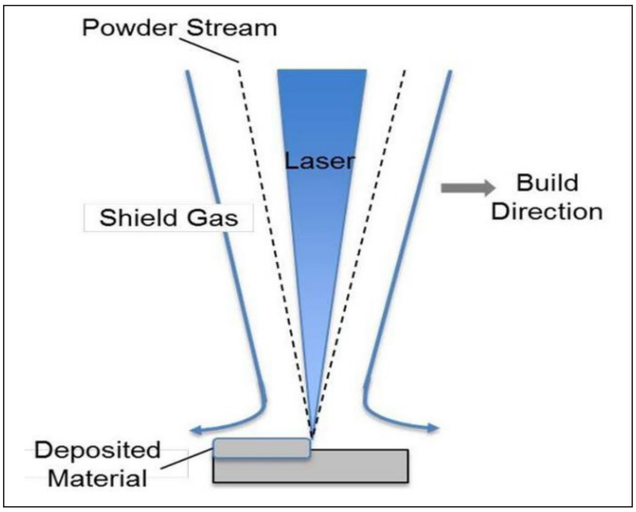

Figure 4: LMP process.

Scanning velocity

By altering the scanning speed and energy input, it is possible to create a microstructure with a higher martensite fraction, a greater number of dislocations, and smaller grain boundaries. As a result, the hardness of the material is ultimately improved. Moreover, prolonging the exposure of the material to elevated temperatures can cause grain coarsening and a decrease in mechanical properties.

Powder feed rate

A higher powder feeding rate also leads to a higher fraction of martensite, a greater number of dislocations, and smaller grain boundaries, resulting in improved hardness of the material. Raising the powder feeding rate leads to thicker layers and a coarser microstructure, resulting in reduced strength and increased ductility of LMD Ti-6Al-4V components. It is still necessary to create mathematical models that can explain how the laser beam and the substance being deposited interact.

Laser power

Increased laser power generally results in greater energy input and reduced cooling rate, resulting in the formation of larger grain sizes and coarser columnar grains. The formation of large grain sizes and coarser columnar grains can reduce the material's resistance to fracture and its tensile strength, resulting from the decrease in cooling rate and the increase in energy input. High laser power increases energy input and decreases cooling rate, which leads to the formation of larger grains and coarser columnar grains, improving material ductility and fatigue properties while decreasing its fracture resistance and tensile strength. Higher laser power can produce larger grain sizes and coarser columnar grains, reducing the material's tensile strength and fracture resistance. This can also lead to a more porous microstructure, enhancing the material's fatigue properties.

EBM technique

In the EBM process, a high-energy electron beam is created and regulated to scan and melt layers of metal powder in accordance with a CAD model. Focusing the electron beam on particular regions of the powder bed causes it to melt and bond with the previously solidified layers by heating it to that degree. The elaborate and complex geometries that may be made with this layer-by-layer technology are difficult or impossible to make using conventional manufacturing techniques. It is often employed to create intricate geometric structures with high precision and accuracy in the aerospace and medical industries. Small melt volumes or melt pools are produced because the melting occurs in layers of pre-alloyed metal powders. These melt pools quickly solidify, allowing the solid component microstructures to develop distinctive, directional growth features that are far from balance in a more traditional thermal sense. And also, the SEBM process operates in a vacuum, providing almost full protection against oxidation and gas contamination.

A sample is put together layer-by-layer, with each layer going through a four-step process of deposition, preheating, melting, and platform lowering.

- Using a rake to deposit a powder layer onto the substrate plate.
- preheating and lightly sintering the powder layer.
- scanning the preheated powder layer with a focused electron beam in accordance with at computer-aided design scheme
- lowering the building platform by a nominal layer thickness and repeating step (1) for layer fabrication

The electron beam power P, scanning velocity v, powder layer thickness t, and hatch distance h are crucial processing parameters that affect the input energy density in SEBM. By using SEBM at various volumetric energy densities, products with a high relative density and higher ultimate compressive strength can be produced.

Laminated object manufacturing

Laminated object manufacturing (LOM) was originally made available for purchase in 1991 by California-based Helisys Inc. (now Cubic Technologies) (Figure 5). It is a fast-prototyping technique that makes models from laminates of metal, plastic, or paper that have been successfully glued together using epoxy. The model or object is then sliced into the required shape using a laser cutter. A heated roller is used to adhere a sheet to a substrate to start the process. The next layers are then carefully sliced and bonded one after the other, either in the order of bonding followed by forming or vice versa. The contemporary sheet of metal is rolled into place, the platform with the final layers' drops, and the platform rises to its original position.

The LOM method, which involves laminating sheet materials, is additive. By roll or single sheet, a whole layer of material is first brought to the platform and laminated to the already-existing stack. Utilizing a heated roller, lamination is performed. A CO_2 laser is used to cut the cross-sectional area's perimeter, one layer deep, after each layer has been laminated. Additionally, the laser "cubes" or dices the extra material to aid in the removal of the final component. The trash is left in place

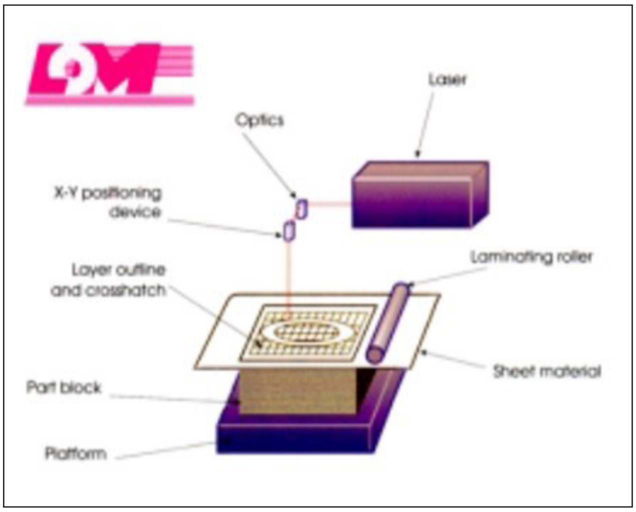

Figure 5: The LOM procedure (provided by Torrance, California-based Helisys, Inc.).

while the structure is being built to act as a support. Lamination and cutting are done one layer at a time until the part is finished. then, the "block".

The present research and development effort is concentrated on employing LOM for direct manufacturing of structural composite components, including continuous fiber polymer composites and ceramic matrix composites. To this goal, popular feedstock components like ceramic tapes and fibre prepregs have been added to the standard LOM process. The curved layer building style was necessary in addition to the creation of novel techniques for feeding, laminating, and cutting these advanced materials. The LOM machine can now construct in a curved-layer-by-curved-layer fashion rather than being restricted to flat layers. To achieve the best mechanical performance, continuous fibre composites can preserve fibre continuity in the plane of curvature thanks to the novel curved layer LOM technique (referred to as "Curved LOM").

Figure 6 depicts the Curved LOM technique. The technique can be used to create either flat or curved panels. A matching tool, or "mandrel," must be provided if a curved panel is desired. Using LOM sticky paper and the normal (flat layer) LOM method, this mandrel can be created. In the Curved LOM machine, the paper mandrel is fixed to the flat building platform. Using a vacuum chuck that is integrated with the laminator, sheets of the desired build material (such as composite prepreg, 0.25 mm thick) are put into a rotational feed table and transported to the mandrel.

Structures made of modern materials that currently need a lot of physical labor to assemble are designed to benefit from the Curved LOM method. Panels used in aerospace or automobiles are two examples of typical components. The three primary types of materials are monolithic structural ceramics, polymer matrix composites, and ceramic matrix composites. Monolithic ceramic and ceramic matrix composites systems have been the focus of the majority of the work done thus far [1-4]. More work is being done to integrate the LOM methodology with cutting-edge, computer-based structural design approaches. The overall research project's objective is to develop a new prototype tool that will allow for the simultaneous evaluation of novel materials, design ideas, and structural component approaches.

The cyclic heat environment experienced during the layer-by-layer lamination process served as the foundation for the mathematical modelling of Curved LOM. For physical and chemical operations in advanced materials, like LOM mandrel and thermoset resin cure Rubberized silicone diaphragm Z-platform flexible heater pad integrated an empty room metallic box Vacuum Vent Line plate hoover. The batch thermal processing-based mathematical models for composites that are currently in use are not appropriate. It was therefore decided to create a brand-new, numerically grounded mathematical model for Curved LOM.

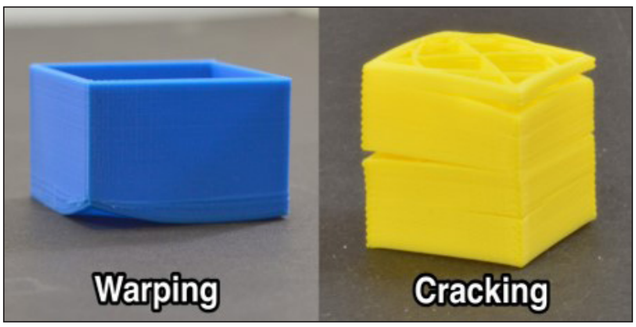

Figure 6: Difference of warping and cracking.

Challenges in Metal 3D Printing and Ways to Overcome

With the assistance of intricate lattice structures and topological optimization, 3D printing reduces several part assemblies into a single part, enabling the production of light metal parts. Metal 3D printing uses the techniques of SLM, EBM, and DMLS to fuse metal powder together to build the completed object layer by layer. In DED, metal wire or powder are fed into the laser to deposit material on top of an already-existing layer. The component is then finished by heat treating it using a technique called binder jetting, in which a liquid binder is shot into a powder over powder bed.

Surface finish

To obtain the necessary surface polish for 3D printed items used in technical applications such as aircraft, automobiles, and medical implants, a sizable amount of post processing is necessary. This post processing includes Computer Numerical Control machining, shot peening, or sand blasting. The PBF method yields pieces that are closer to their ultimate form. Therefore, it is possible to utilize fine powder with thin layer thickness to get a greater surface smoothness, which raises the price of the component. In order to obtain the desired surface finish at a reasonable price, the best balance between cost and surface finish must be determined.

Porosity

Small cavities known as porosity can be seen on printed parts (Figure 7). These pores are a result of the 3D printing technique or the powder that was utilized. These tiny flaws cause the part to become less dense, which increases the risk of fatigue and cracking. When the layer thickness of the part's layer is greater than the size of the powder particles and when

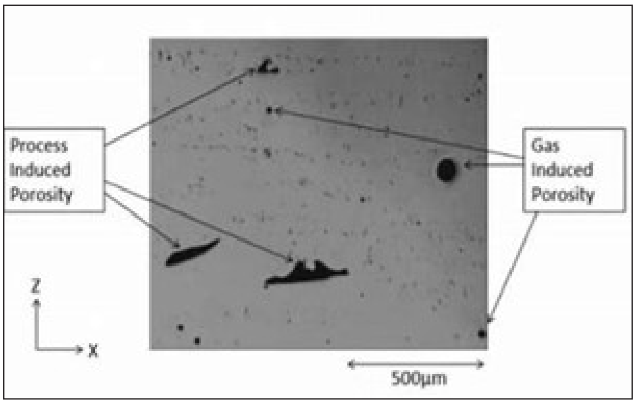

Figure 7: Morphology of porosity.

not enough metal flows into the appropriate melt zone, pores are present. Process variables including power, laser spot size and scan speed must be tuned for a specific material and component to minimize porosity in the printed part. By using post-processing techniques like hot isostatic pressing and infiltration process, DLMS porosity is reduced.

Density

Low density in the component due to high porosity causes fatigue failure and cracking. Density above 99% is needed for critical applications. The part's density can be increased and the powder's flowability is improved by using spherical powder particles. Wide powder particle distribution causes fine particles to fill in between the larger parts, increasing the component's overall density but decreasing the powder's flowability. AM process parameter manipulation is used to control density.

Warpage

Thermal stress will form in the substrate if the initial printing layer is not properly bonded to it. If this stress exceeds the material's maximum strength, the substrate will start to wrap, which will cause warpage of the printed component (Figure 8). Then, the recoated and the printed metal portion continually collide. And more strains are created because of the material's variable thickness. The right number of supports must be positioned correctly to minimize the warpage of the part. Either through the design of an experiment or by trial and error, the appropriate number of supports and their placement must be established. Support structure is crucial because it helps prevent printed materials from deforming.

Residual stress

Residual stress is created during metal printing process because of the cycles of heating and cooling. Additionally, the component's strength declines due to excessive residual stress in the metal, which causes cracks to form and the substrate to distort. The area where the part and substrate meet has the most residual stress. Support structures are offered hotter than the substrate to lessen residual stress. Heat treatment is applied to the printed portion, support structure, and substrate.

Cracking

When melted metal solidifies or when a concentrated area is heated to a hot temperature, cracks can form. Delamination, which causes crack formation between the layers, occurs Heating the substrate will prevent delamination, and post-processing will remove most cracks. By altering process variables like laser power, scan speed, and energy density, crack formation can be prevented.

Conclusion

3D metal printing is a disruptive technology that might to revolutionize the manufacturing industry. The various methods have their own advantages and disadvantages, and they are used based on the application. Apart from this some key challenges need to be addressed such as improving mechanical characteristics of metal 3D-printed components, making it cost-effective, increasing the speed of 3D printing. Metal 3D printing has the ability to produce intricate, unique pieces that would be challenging or impossible to make using conventional techniques. The price of metal 3D printing is anticipated to drop, and the quality of metal 3D printed parts to rise as technology advances. This makes metal 3D printing process more accessible to a wider range of various industries and applications.

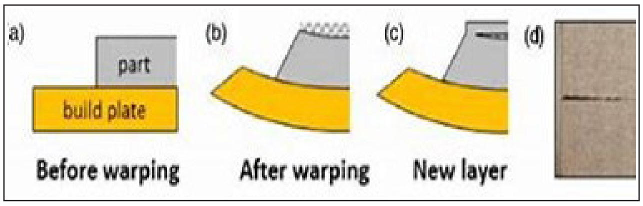

Figure 8: Warpage.

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None.

Conflict of Interest

None.

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