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The Role of Metal Additive Manufacturing

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Abstract: Additive manufacturing, a layer-based manufacturing process, has revolutionized the production of parts directly from 3D models. This paper presents a comprehensive review of key technologies utilized in metal additive manufacturing, with a specific focus on the influence of critical process parameters on the resulting part's microstructure and mechanical properties. The study encompasses various materials, including aerospace alloys such as titanium (TiAl6V4 "UNS R56400"), aluminum (AlSi10Mg "UNS A03600"), and iron- and nickel-based alloys, including stainless steel 316L ("UNS S31603"), Inconel 718 ("UNS N07718"), and Invar 36 FeNi36 ("UNS K93600").

Keywords: Metal additive manufacturing, FDM, selective laser melting, additive manufacturing processes, rapid manufacturing, aerospace industry.

Introduction: Additive Manufacturing (AM), as defined by ASTM International, is a transformative process that involves creating objects by joining materials based on 3D model data, layer by layer, in contrast to traditional subtractive manufacturing methods. The versatility of AM has led to various classifications in the literature, including the base material used, such as polymers, ceramics, and metals differentiation between indirect and direct processes based on bonding methods and categorization by the state of the raw material input, such as liquid, molten, powder, and solid layer processes. This paper provides an overview of the metal AM processes, elucidating their benefits and applications. Additionally, it presents a comprehensive review of how AM process parameters influence material properties, impacting the performance and characteristics of the final components. The main focus lies on the challenges hindering the widespread industrial adoption of AM, particularly in critical sectors like aerospace.

Additive Manufacturing Process:

Additive Manufacturing (AM), commonly known as 3D printing, is a transformative process that fabricates objects by adding material layer by layer, based on a digital 3D model. This revolutionary manufacturing approach stands in contrast to traditional subtractive methods that involve removing material from a solid block to achieve the desired shape. The additive nature of the process allows for greater design freedom, complexity, and customization, making it suitable for a wide range of applications across various industries.

ASTM International categorizes the AM processes into seven main categories, according to the adhesion and bonding method. These categories are: (i) VAT photo polymerization, (ii) Material jetting, (iii) material extrusion, (iv) powder bed fusion, (v) binder jetting, (vi) direct energy deposition, and (vii) sheet lamination. VAT polymerization or material jetting could be used in liquid AM processes, while material extrusion could be used in filament processes. Powder AM processes coulduse powder fusion, binder jetting, or direct energy deposition for binding the powder particles. Since then various processes have been introduced. Fig. shows a classification of various AM processes according to the state of the raw material. In this section, these AM processes are explained.

VAT Photo polymerization: This category includes processes that use liquid photopolymer resin as the raw material. The resin is solidified or cured layer by layer using ultraviolet (UV) light or other forms of light exposure.

Material Jetting: Material jetting involves depositing small droplets of liquid photopolymer or other materials onto the build platform. These droplets solidify quickly through UV light exposure or other curing methods.

Material Extrusion: Material extrusion, also known as Fused Deposition Modeling (FDM), employs a filament of thermoplastic material as the raw feedstock. The filament is heated and extruded through a nozzle, forming layers to build the object.

Powder Bed Fusion: Powder bed fusion processes use a bed of powdered material, typically metal or plastic, as the raw feedstock. A heat source, such as a laser or electron beam, selectively fuses the powder particles together, layer by layer.

Binder Jetting: In binder jetting, a liquid binder is selectively jetted onto a powder bed, binding the particles together to form the object. After printing, the part is typically sintered to further solidify the structure.

Direct Energy Deposition: Direct energy deposition involves depositing material, usually in the form of powder or wire, onto a substrate using a focused energy source, such as a laser or electron beam. This process is commonly used for repair or cladding applications.

Sheet Lamination: Sheet lamination processes join layers of material together using heat, pressure, or adhesive. Sheets of material are stacked, and each layer is cut to the desired shape before bonding to form the final object.

Material Extrusion:

Fused deposition manufacturing: Fused Deposition Modeling (FDM) is an AM process in which two separate nozzles, one for model material and another for support material, are used to build a 3D model designed using a CAD tool. In a typical FDM system, the build material is melted and deposited from the build nozzle to create the part layer-by-layer as shown in Fig. The support material is added to each layer to support the built layer, but it needs to be removed at the end of thebuilding process. One of the limitations in the FDM process is the dimensional inaccuracies and poorsurface finish of the fabricated parts. Predicting the dimensional accuracy as a function of process parameters is a heavily researched area within the FDM research field. In addition, mechanical and thermal properties are big challenges not only in the FDM process, but in most AM metal processes. For this reason, many researchers focus on studying the mechanical and thermal properties of AM metal parts.

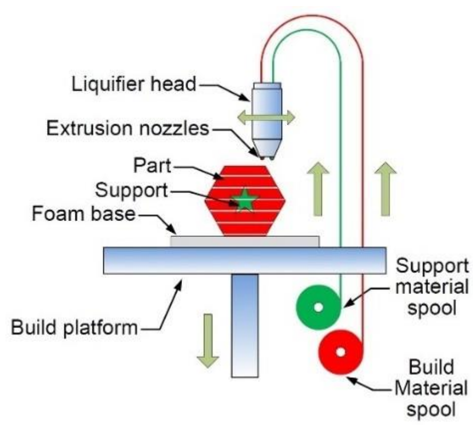

Fig. Fused deposition modeling

Powder Bed Process:

Selective Laser Melting: Full melting of powders strives to produce fully dense objects with mechanical properties comparable to bulk materials. The development of the Selective Laser Melting (SLM) process mirrors the process of SLS with that goal in mind. All metals may be candidates but some act differently when processed. Such differences include reactions to laser absorption, different surface tensions, and different viscosities. These complications limit the range of available SLM metals. SLM powders can be broken down into two categories: single material powders or alloyed powders. Single material powders consist of strictly one type of metal, such as pure titanium. In this case, tests show an almost 100% part density, however high thermal stresses can cause cra

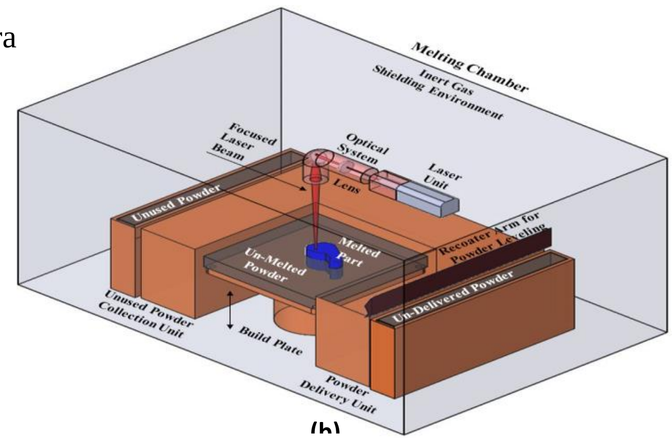

Fig. selective laser melting

Alloyed powders consist of alloyed materials such as Ti-6Al-4V and steel powders. The mechanical properties of these materials are comparable to bulk material apart from ductility, which is significantly reduced. A big benefit of SLM is the ability to process non-ferrous metals such as titanium, aluminum and copper. As the process uses higher energy, problems arise with instabilities in the melt pool along with part shrinkage.

Application of metal Additive Manufacturing

Metal Additive Manufacturing (AM) has garnered widespread attention and adoption in various industries due to its ability to create complex geometries, lightweight structures, and customized components. Some of the key applications of metal additive manufacturing include:

Aerospace: Metal AM is extensively used in the aerospace industry for fabricating lightweight and high-performance components. Critical parts, such as aircraft engine components (e.g., turbine blades and fuel nozzles), brackets, and heat exchangers, can be designed with intricate cooling channels and optimized shapes for enhanced efficiency and reduced fuel consumption.

Healthcare: Medical implants, such as hip and knee replacements, are often produced using metal AM, allowing for personalized designs that better match the patient's anatomy. Additionally, dental applications, surgical instruments, and prosthetics can benefit from the high accuracy and design freedom offered by metal AM.

Automotive: Metal AM is employed in the automotive industry for rapid prototyping, tooling, and lightweight structural components. Complex brackets, engine parts, and customized jigs and fixtures can be manufactured using metal AM, reducing production time and costs.

Tooling: The production of tooling, including molds, dies, and tool inserts, benefits from the design flexibility and quick turnaround times offered by metal AM. Complex tool geometries can be produced without the constraints of traditional machining processes, enabling faster prototyping and production cycles.

Influence of process parameter

From the above survey of AM processes, FDM, DED, SLM, and EBM are the most commonly used processes for metal fabrication. In this section, the influence of process parameters on the microstructure and mechanical properties of selected aerospace materials are reviewed.

Titanium Alloys: Many researches are focusing on studying the characteristics of titanium TiAl6V4 (UNS R56400) produced by different AM processes to meet aerospace standards. A study showed that the mechanical and fatigue behaviors of the SLM TiAl6V4 parts are significantly affected by the internal voids as well as the residual stresses in the parts produced. The tensile strength and fatigue strength are strongly affected by the pores size, however the crack growth is influenced by the residual stresses. Another study demonstrated that the microstructure of the SLM TiAl6V4 components also alters the mechanical properties of these parts. The SLM process parameters such as scanning parameters, scanning strategies, and laser melting parameters exhibited a strong influence on the surface quality, voids characteristics, microstructure, and mechanical properties of TiAl6V4 parts. Moreover, few studies were performed to find the optimum SLM process parameters for fabricating TiAl6V4 parts suitable for the aerospace industry. Similar studies performed using other AM processes such as DED and EBM achieved similar results. In EBM production of TiAl6V4, a function is developed to control the beam speed and energy during the fabrication process in order to enhance the thermal properties of the parts produced.

Aluminum Alloys: Although AM has gained considerable popularity in aerospace and automotive applications, it still faces many challenges with processing aluminum alloys. Many investigations were performed to find the process parameters required to produce high dense aluminum AlSi10Mg (UNS A03600) parts by SLM. Few studies focused on investigating the quality of the aluminum parts produced by AM processes. These studies showed that the microstructure of the SLM AlSi10Mg and AlSi12 parts has a significant effect on the mechanical properties such as fatigue behavior, strength, elongation, etc. Moreover, the microstructure of these parts is influenced by the imperfections formed during the process and the post-processing procedures. The AlSi10Mg still manifests fatigue strength lower than that of a corresponding wrought material. Internal voids and/or large internal precipitated particles serve as fatigue crack initiation sites. However this material also does show a very fine microstructure and anisotropic mechanical properties along the building direction.

Iron- and Nickel- Based Alloys: Stainless steel 316L (UNS S31603) is the most commonly used material in powder-based AM processes. Starting from the raw material, the powder grain size affects the density and consequently the mechanical properties of the produced parts. In SLM of stainless steel 316L, some studies showed that point distance, exposure time, scan speed, layer thickness, and building direction have a strong influence on the quality of the parts produced. These parameters should be controlled during the fabrication process in order to get reasonable surface finish and mechanical properties. AM technology opens the door for fabricating special alloys such as nickel-based alloys. Some studies showed that AM produced Inconel 718 (UNS N07718) parts contained small cracks that may affect mechanical properties in all directions especially in the building direction. These cracks can be attributed to the phase transition and the formation of columnar dendrites during the melting process. On the other hand, few studies illustrated the selection of the process parameters for fabricating dense parts from Invar 36 (UNS K93600).

Conclusion

In conclusion, this paper has provided a comprehensive review of various additive manufacturing processes and their applications. It is evident from the survey that additive parts may exhibit distinct characteristics compared to traditional wrought parts, including the presence of defects such as voids, inadequate adhesion between layers, and substandard mechanical and fatigue properties. However, despite these challenges, metal additive manufacturing has demonstrated immense potential in revolutionizing product design and manufacturing.

The literature indicates several research and development priorities to further enhance the capabilities and reliability of metal additive manufacturing processes. Some of the key research areas include studying the influence of process parameters on surface features, mechanical properties, and material characteristics through modeling and experimentation. Additionally, developing new materials tailored to the capabilities of additive processes is crucial for expanding the range of applications and unlocking innovative designs.

Establishing rules and protocols for designing specifically for additive manufacturing is essential to fully leverage the technology's potential. Real-time process control is another vital aspect that needs attention to ensure consistent and reliable production. Furthermore, exploring hybrid manufacturing and multi-material additive manufacturing holds promise for creating complex and versatile components.

While newly emerging metal additive manufacturing processes face limitations and challenges compared to established subtractive manufacturing methods, efforts are underway to address these issues. Process repeatability, complex thermal stresses, and material microstructural implications are significant hurdles to overcome, especially in aerospace applications. Post-processing techniques have been widely adopted to refine the quality of additive parts, but optimizing and controlling process parameters to produce high-quality parts present an alternative and promising approach.

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