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Research Progress on Support-Free Metal 3D Printing Technology Based on Powder Bed Fusion

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Abstract. In traditional metal additive manufacturing, the presence of support structures leads to issues such as material waste, complex post-processing, and limited design freedom, significantly restricting the potential of this technology in the fabrication of complex structures. To overcome this bottleneck, support-free metal 3D printing technology has become a research hotspot in recent years. This paper systematically explores the powder bed fusion support-free metal 3D printing technology, with a focus on analyzing the heat transfer characteristics and molten pool dynamic behaviors during the printing process. It proposes strategies for scanning path optimization and synergistic control of process parameters, and evaluates the material adaptability of titanium alloys, stainless steel, high-temperature alloys, and aluminum alloys. The research results indicate that thermodynamic behavior directly affects the forming quality, and process optimization can effectively control defect formation. Significant performance differences are observed across different materials. The paper also highlights the technical challenges faced by this technology, such as residual stress control, and provides an outlook on future development directions. This study offers a theoretical foundation for the engineering application of support-free metal 3D printing technology.

Keywords: Powder Bed Fusion, Support-Free, Metal 3D Printing, Thermodynamic Mechanism, Process Optimization.

1. Introduction

Metal 3D printing technology, as an important branch of additive manufacturing, plays an increasingly critical role in modern manufacturing. In the aerospace industry, GE (General Electric) of the United States has adopted electron beam powder bed fusion (EB-PBF) technology to mass-produce titanium-aluminum low-pressure turbine blades for aircraft engines, successfully applying them to the GE9X engine, which achieved its maiden flight [1]. In the biomedical field, Arcam (now part of GE Group) in Sweden has developed orthopedic artificial hip implants (acetabular cups) using EB-PBF technology, which are now widely used in clinical practice. Statistics show that one in every 30 hip surgeries involves the use of this implant. Additionally, Zhongnuo Hengkang Company in Beijing, China, uses EB-PBF technology to produce interbody fusion devices, achieving a printing output of 800-1000 units in a single print by employing a stacking printing

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process, significantly improving the production efficiency of medical implants. The use of support structures in traditional powder bed fusion metal 3D printing poses numerous drawbacks, and support-free metal 3D printing technology effectively avoids these issues, making it a key focus of current research [2].

This paper aims to systematically analyze the technology from multiple key perspectives, promoting a deeper understanding and application of it. Additive manufacturing technology has developed rapidly in recent years, with its applications becoming increasingly widespread across various fields. As an important component of this technology, powder bed fusion has gained significant attention, particularly in the research of its support-free printing technology.

2. Thermodynamic mechanism

2.1. Thermal conduction characteristics

Thermal conduction is the dominant mode of heat transfer in this process. The laser or electron beam (the heat source) transfers energy to the metal powder. Once the powder absorbs the energy, its temperature rises quickly and melts to form a molten pool. Heat is then conducted from the center of the molten pool to the surrounding unmelted powder and the solid substrate. The rate of heat conduction depends on the thermal conductivity of the material, the packing density of the powder, and the temperature gradient. Titanium alloys, for instance, have relatively poor thermal conductivity, so heat cannot easily escape during the printing process, leading to larger molten pools and slower solidification. On the other hand, stainless steel has better thermal conductivity, allowing for rapid heat transfer, resulting in a smaller molten pool and faster solidification. The thermal conduction behavior in metal additive manufacturing significantly affects part quality, and relevant research is constantly progressing [3].

2.2. Molten pool behavior and stability

The formation and evolution of the molten pool is the key aspect of the thermodynamic mechanism. The size, shape and flow state of the molten pool are affected by the laser power, scanning speed, powder properties, etc. With the increase of laser power and the decrease of scanning speed, the energy input to the powder bed increases, resulting in the increase of the depth and width of the molten pool. Otherwise, the molten pool becomes smaller. The liquid metal in the molten pool flows under the effect of surface tension, gravity and vapor pressure. The flow helps to melt and fuse the powder completely, which ensures the quality of the metallurgical bonding. In the support-free printing of overhanging structures, the surface tension of the molten pool is particularly important because it can counteract gravity to a certain extent, keep the molten pool stable and avoid the liquid metal dripping to realize the support-free forming. The study of the behavior and stability of the molten pool in powder bed fusion is fundamental for process optimization [4].

2.3. Solidification process and microstructure evolution

Phase transformation and microstructure evolution in the solidification process areclosely related to thermodynamics. With continuous heat dissipation, the temperature of the molten pool decreases gradually. When the temperature drops below the meltingpoint of the metal, the liquid metal starts to solidify. The solidification rate and coolingrate have a significant impact on the size and shape of the grains. Fast cooling can refine the grain, forming fine equiaxed or columnar grains, which improves the mechanicalproperties of the part. Slow cooling may lead to coarse grains and reduce the

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performance of the part. In support-free printing, the cooling rate in some areas is different because there is no heat dissipation from the support structure, which affects the solidification microstructure and needs to be adjusted carefully through process parameters. Different solidification processes produce different microstructures, which in turn affect the performance of metal parts. It is an important research field in the additive manufacturing technology [5].

3. Process optimization strategies

3.1. Scanning path optimization

Scanning path optimization is one of the most important process optimizations for support-free metal 3D printing based on powder bed fusion. Traditional unidirectional or raster scanning is easy to realize, but the single heat input direction and concentrated energy accumulation easily cause excessive local temperature gradient, leading to the concentration of residual stress and warpage deformation of parts, which greatly affects the forming quality and dimensional stability. To solve this problem, some more complicated path planning strategies, such as zonal scanning, staggered scanning, or spiral scanning, are used in recent studies. The scanning paths can effectively disperse the influence of the heat source, making the heat distribution more uniform, which can greatly reduce the accumulation of residual stress and improve the geometric accuracy of parts. Taking printing structure with overhang or thin-walled features as an example, a well-designed scanning sequence and direction can first form an edge support frame, which can improve the structural stability of these regions and prevent molten pool collapse or deformation. In addition, the scanning path optimization can also improve the overlap of the molten pools and the consistency of solidification, reducing the porosity and lack of fusion and further improving the mechanical properties and surface quality of the parts [6].

3.2. Coordinated adjustment of process parameters

The coordination and adjustment of process parameters are critical to obtain high-quality, support-free printing. Laser power, scanning speed, layer thickness, scanning spacing, etc. are related to each other and need to be optimized as a whole. Generally speaking, for structures with small overhang angles, the laser power can be appropriately reduced and the scanning speed increased to reduce the fluidity of the molten pool and avoid metal flow loss. On the contrary, for more complex overhanging structures, the laser power should be increased, and the scanning speed decreased, so that the powder is completely melted and a stable molten pool is formed. The choice of layer thickness should also be based on the accuracy requirements and structure characteristics of the part. The thinner the layer thickness, the better the surface quality, but the lower the printing efficiency, and vice versa. Through a large number of experiments and data analysis, the relationship between process parameters and part quality can be established, and the optimal combination of parameters can be provided for support-free printing of different structures. In metal additive manufacturing, the selection and coordination of process parameters are essential to ensure printing quality [6].

3.3. Preheating and post-heat treatment processes

Preheating and post-heat treatment can effectively improve the performance of parts. Preheating the powder bed before printing reduces the temperature gradient between the molten pool and the surroundings, which minimizes the formation of thermal stresses.The selection of preheating temperature depends on the material property. For instance, the preheating temperature for high

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strength steels can be selected from 200- 300Csuperscript200300degreeC200-300^{\circ}\mathrm{C}. Post-heat treatment is used to eliminate residual stresses and improve the mechanical properties of the parts.Commonly used post-heat treatment includes annealing, normalizing, aging treatments, etc., which control the heating temperature, holding time, and cooling method to manipulate the microstructure and properties of the parts. For example, annealing treatment for the support-free printed 316L stainless steel parts can reduce the residual stresses and improve their plasticity and toughness. The heat treatment process has been extensively used to improve the performance of parts in metal AM [7].

3.4. Application of real-time monitoring and feedback systems

The use of real-time monitoring and feedback systems is an important guarantee for process optimization. The temperature field, molten pool state, and powder distribution during the printing process can be monitored in real-time using infrared cameras, high-speed cameras, and other instruments. The information obtained from monitoring is fed back to the control system so that the process parameters can be adjusted in a timely manner. For instance, when problems such as too large or too small molten pool, abnormal temperature rise, etc., are detected, the laser power, scanning speed, etc., can be automatically adjusted to ensure the stability of the printing process. This intelligent process optimization helps improve the reliability and consistency of support-free printing and reduce the rejection rate. With the development of technology, the application of a real-time monitoring system in additive manufacturing is becoming more mature [4].

4. Material system adaptability research

4.1. Titanium alloys

Titanium alloys are widely used in the aerospace and medical industry because of their high strength, low density and good corrosion resistance. Titanium alloy powders have good flowability and sinterability, which makes them suitable for powder bed fusion. During support-free printing, the low thermal conductivity of titanium alloys enables themolten pool to stay in a liquid state for a longer time, which benefits the formation of overhanging structures, but also leads to higher residual stresses. By adjusting the process parameters and using proper heat treatment processes, the performance of support-free printed titanium alloy parts can be greatly improved. For instance, during the support-free printing of Ti6Al4V titanium alloy, the density and mechanical properties of the printed parts can be greatly improved by properly controlling the laser power and scanning speed. Titanium alloys are one of the most commonly used materials in metal AM, and the research on their printing performance is relatively mature [8]. The team led by Zhang Zhefeng developed a new post-processing technology (NAMP process) for Ti-6Al-4V titanium alloy. This technology eliminates micro-pores and coarse structure by accurately controlling the internal structure and defects of the material, greatly enhancing the fatigue resistance of titanium alloys under complex stress ratios. The fatigue strength of this process exceeds that of known metallic materials, which provides important support for the application of support-free printed titanium alloys in high-end precision fields [9].

4.2. Stainless steel

Stainless steel, with good plasticity, toughness and corrosion resistance, is one of the commonly used materials in powder bed fusion printing. The powder of 316L stainless steel has a uniform

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particle size distribution, good fluidity and easy spreading. In the support-free printing, stainless steel has a relatively high thermal conductivity, a rapid cooling rate and good molten pool stability, which is conducive to the printing of relatively simple support-free parts. For a more complex overhanging structure, it needs accurate control of process parameters to avoid cracking and deformation. Relevant studies show that by changing the scanning path and optimizing the layer thickness, the surface quality and dimensional accuracy of the support-free printed parts of 316L stainless steel can be improved. Stainless steel has been widely used in additive manufacturing, and the relevant process is still advancing with continuous research [7]. In the support-free printing research of 316L stainless steel carried out by China FAW Group Corporation, the laser power, scanning speed, and layer thickness parameters were systematically optimized to realize the support-free forming of the structure with the overhang angle as low as 30. It was pointed out in the study that by means of zonal scanning and real-time temperature monitoring, the residual stress could be reduced and the surface quality could be improved (the Ra value was controlled below 3.2 m\mu m), which provided the process standard and application case for the support-free manufacturing of automobile components, such as the lightweight structural part [10].

4.3. High-temperature alloys

High-temperature alloys maintain good mechanical properties in high-temperature environments and are widely used in the manufacturing of high-temperature components, such as those in aerospace engines. However, the support-free printing of high-temperature alloys is challenging due to their high melting points and low thermal conductivity, which can lead to significant thermal stresses and cracking during the printing process. For example, IN718 high-temperature alloy requires strict control of laser energy input and cooling rate during support-free printing to prevent thermal cracking. By adding appropriate alloying elements and optimizing process parameters, the printing performance of high-temperature alloys can be improved, expanding their application in support-free printing. Additive manufacturing technology for high-temperature alloys holds significant potential for applications in the aerospace industry [6]. The experimental team led by Li Dichen conducted a systematic study on the support-free forming of K418 nickel-based high-temperature alloy, developing a multi-scale scanning strategy and zonal energy control method. The study demonstrated that by adopting a variable-angle staggered scanning path and localized thermal field management, support-free manufacturing of complex turbine blade cooling channels with overhang angles as low as 25° was successfully achieved. The parts' high-temperature endurance performance reached over 90% of the forged standard, providing crucial technological support for the integrated forming of aerospace engine hot-end components [11].

4.4. Aluminum alloys

Aluminum alloys have advantages such as low density and good thermal conductivity; however, they present challenges in powder bed fusion support-free printing due to their high reflectivity and susceptibility to oxidation. The high reflectivity of aluminum alloys leads to low energy utilization, requiring higher laser power to achieve powder melting. At the same time, aluminum alloys are prone to oxidation during the melting process, forming an oxide layer that affects the flowability of the molten pool and metallurgical bonding. By using surface treatment technologies to reduce the reflectivity of aluminum alloy powders and printing under inert gas protection, the success rate of support-free printing of aluminum alloys can be improved. Research on support-free printing of aluminum alloys is still ongoing, aiming to develop process methods suitable for large-scale

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applications. Additive manufacturing research on aluminum alloys is gradually progressing to meet the needs of various fields [7]. The China Academy of Launch Vehicle Technology has made progress in support-free printing of aluminum alloys (such as AlSi10Mg). By adjusting powder properties, optimizing laser-powder interaction, and employing intelligent path planning, the support-free forming of complex overhanging structures was achieved, with surface precision reaching the millimeter level and a 60% reduction in post-processing workload. This technology has been applied in the manufacturing of large aerospace modules and shells and has been flight-tested, proving the feasibility and reliability of support-free printing with aluminum alloys [12].

5. Technical challenges and future outlook

5.1. Technical challenges

Control of residual stress remains a core challenge. In support-free printing of complex structures, uneven stress distribution can lead to deformation and cracking of parts, especially for large components and thin-walled structures. This requires more precise thermodynamic analysis and process control methods. Residual stress issues are a common challenge in metal additive manufacturing [7].

Surface quality and precision still need further improvement. Parts produced by support-free printing often exhibit high roughness and noticeable step effects, which can affect both the functional performance and aesthetic appearance of the parts. Although post-processing can improve surface quality, it increases both cost and time. The challenge is how to achieve high-quality surfaces directly during the printing process. Surface quality and precision are important indicators of the quality of additive manufacturing parts [6].

The limitations of material systems are also quite significant. Currently, the types of materials suitable for support-free printing are relatively limited. The support-free printing processes for many high-performance metal materials are still not fully developed, making it difficult to meet the diverse needs of different industries. Additionally, the high cost of materials restricts the large-scale application of this technology. Expanding the material systems is an important direction for the development of additive manufacturing technology [8].

Insufficient process stability and repeatability remain barriers to industrial applications. Since the powder bed fusion support-free printing process is influenced by various factors, even small fluctuations in process parameters can lead to significant variations in part quality, making it difficult to ensure consistency in mass production. Establishing comprehensive process standards and quality control systems is key to addressing this issue. Process stability is crucial for the industrial application of additive manufacturing [3].

5.2. Future outlook

In terms of materials, it is expected that more new alloy materials suitable for support-free printing will be developed. Through material design and modification, the printing performance and service properties of materials can be enhanced while reducing material costs. At the same time, support-free printing of composite materials will also become a research hotspot, aiming to achieve an optimal combination of material properties. Innovations in materials will drive the further development of additive manufacturing technology [8].

The level of equipment intelligence will continue to improve. The integration of advanced sensors, artificial intelligence, and big data analytics will enable real-time monitoring, intelligent

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diagnosis, and adaptive control of the printing process. For example, machine learning algorithms can predict potential defects in parts and automatically adjust process parameters to compensate, thus enhancing the stability and reliability of support-free printing. Intelligence is a key trend in the development of additive manufacturing equipment [4].

Process innovation will continue to advance. The development of more advanced scanning technologies and energy sources, such as the optimized application of ultrashort pulsed lasers and electron beams, will improve the precision and controllability of energy input. New printing modes, such as multi-nozzle collaborative printing and in-situ repair technologies, will be explored to expand the application range of support-free printing. Process innovation is the core driving force behind the progress of additive manufacturing technology [6].

Applications across multiple fields will continue to expand. In the aerospace industry, more complex and higher-performance support-free parts will be manufactured to reduce the weight of aircraft and improve fuel efficiency. In the medical field, customized support-free metal implants will become more widespread, enhancing treatment outcomes. In the automotive manufacturing industry, support-free printing will be used to produce lightweight, high-performance automotive components, driving the upgrade of the automotive industry. The application fields of additive manufacturing technology are continuously expanding [13].

6. Conclusion

Powder bed fusion support-free metal 3D printing technology has achieved significant research outcomes in thermodynamic mechanisms, process optimization, and material adaptability. However, it still faces technical challenges such as residual stress, surface quality, material limitations, and process stability. Through in-depth research on thermodynamic behavior, optimization of process strategies, and expansion of material systems, this technology is expected to make even greater breakthroughs in the future. With the development of intelligent equipment and the expansion of applications across various fields, powder bed fusion support-free metal 3D printing technology will bring revolutionary changes to manufacturing, driving industrial production towards higher efficiency, better quality, and greater personalization. The development prospects of additive manufacturing technology are vast, and as an important component of this field, powder bed fusion support-free metal 3D printing technology will play an increasingly important role.

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