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A Review of Research Progress and Applications of Metal Additive Manufacturing Technology

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Abstract. Metal additive manufacturing is a technology based on the principle of layer-by-layer accumulation.It offers core advantages such as high design freedom, high material utilization rate and the ability to achieve integrated forming of complex structures. It has become a key manufacturing technology in fields such as aerospace, biomedicine, and high-end equipment. This paper systematically reviews the forming principles and applicable scenarios of three mainstream metal additive manufacturing technologies: laser powder bed fusion, electron beam powder bed fusion, and directed energy deposition. It elaborates on the compatibility characteristics and engineering applications of core materials such as titanium alloys, superalloys.It summarizes the core advantages of this technology and the current industry challenges it faces, such as cost and performance consistency. Finally, it outlines the development trends toward large-scale, more efficient and more diverse materials, aiming to provide references for research and engineering applications in the field of metal additive manufacturing.

Keywords: metal additive manufacturing, powder bed fusion, directed energy deposition, quality control, engineering applications

1. Introduction

Metal additive manufacturing (3D printing) is an advanced manufacturing technology that uses digital model to directly produce dense metal parts through layer-by-layer deposition .

Metal additive manufacturing fundamentally differs from traditional forging, casting, and machining in core logic.Regarding mold dependency, additive manufacturing eliminates the need for molds and can be directly driven by digital models, while traditional manufacturing heavily depends on molds and specialized tools. In design freedom, additive manufacturing enables direct forming of complex internal cavities, lattice structures, and integrated irregular shapes, overcoming geometric constraints imposed by tool accessibility and mold opening in traditional machining. Conversely, intricate structures in conventional manufacturing often require disassembly into multiple parts for assembly. For material utilization rates, additive manufacturing typically achieves over 90% efficiency, with un-melted powder recoverable and reusable after sieving, whereas traditional machining usually yields less than 30%, and casting/forging processes only reach 60%-80%. In development cycles, additive manufacturing allows direct prototyping post-design, reducing product

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development time by over 70%, while traditional methods entail mold development, trial runs, and iterative modifications, resulting in prolonged cycles and poor adjustment flexibility.

After the first commercial 3D printing equipment was introduced in 1988, the industry began to explore the additive forming path of metal materials.In the 21st century, breakthroughs have been made in key technologies such as high-power lasers, electron beams, and precision control. The three core technologies of laser powder bed fusion, electron beam powder bed fusion, and directed energy deposition have gradually matured, achieving direct forming of high-performance dense metal parts and completing the leap from "rapid prototyping manufacturing" to "direct manufacturing of high-performance structural parts".

This article focuses on the mainstream technology system of metal additive manufacturing, including three mainstream processes.It summarizes the additive adaptation characteristics of commonly used metal materials in engineering. And it focuses on analyzing their typical applications in the aerospace, biomedical, and automotive industries, objectively evaluating their technological advantages and industry challenges, and looking forward to future development trends.

2. Mainstream metal additive manufacturing technology and principles

2.1. Laser powder bed fusion (LPBF)

LPBF is currently the most widely used metal additive manufacturing technology. The core process flow is as follows: the powder spreading device evenly spreads a layer of metal powder on the build substrate, and the laser beam selectively scans the powder layer according to the preset path of the slicing model, causing the metal powder to completely melt and form a molten pool. After rapid solidification, the molten pool forms a metallurgical bond with the underlying layer; After the scanning is completed, the forming platform is lowered by one layer thickness, and the process of powder spreading scanning and solidification is repeated until the entire part is formed. The unmelted powder can be recycled and reused after screening.

The core features of this technology are high forming accuracy, a density of over 99.9%, the ability to achieve extremely complex and fine structure forming, a cooling rate of up to 10^{3}~10^{6} K/s, and easy access to non-equilibrium microstructure and excellent mechanical properties; Its limitation lies in the limited size of the forming chamber, which is mostly used for the manufacturing of small and medium-sized precision parts, and it has poor adaptability to the forming of high reflective aluminum alloys and copper alloys.It is mainly used in aerospace precision structural components, medical implants, mold conformal cooling channels and other scenarios [1].

2.2. Electron beam powder bed fusion(EB-PBF)

EB-PBF uses high-energy electron beams as a heat source to complete layer by layer powder melting and forming in a high vacuum environment. Compared with LPBF, its core difference lies in the fact that the electron beam achieves scanning through electromagnetic field deflection, with an energy utilization rate of over 70%, much higher than the 10% -20% of laser; The vacuum environment can prevent material oxidation and is suitable for highly active and high melting point materials; During the forming process, the preheating temperature of the powder can reach 600-1000 °C, significantly reducing the residual stress and cracking risk of the parts.

Table 1. Additive forms and main characteristics of different metal additive manufacturing technologies

category		Additive form	Technical advantage	Technical disadvantage
Laser additive manufacturing technology	Selective Laser Meltingtechnology	metal powder	High precision, capable of simultaneously processing and manufacturing multiple laser beams	Slow forming rate, low laser absorption rate of aluminum alloy, and small forming size
	Laser Melting Deposition Technology	metal powder	The forming size is relatively large, which can be used for part repair and material surface modification	Low precision, requiring secondary processing
Electron Beam Additive Manufacturing Technology	Electron beam selective melting technology	metal powder	High precision, high internal quality	It needs to be manufactured under vacuum conditions, with smaller forming dimensions
	Electron Beam Free Forming Manufacturing Technology	metal powder	Fast forming speed and high internal quality	Low precision, requiring secondary processing

The core advantage of this technology is its wide forming window for refractory and highly active metals, good metallurgical quality, low residual stress, and suitability for forming materials such as titanium aluminum intermetallic compounds, nickel based high-temperature alloys, and refractory metals; The limitations lie in the high equipment cost, complex vacuum environment operation process, slightly lower forming accuracy than LPBF, and high commercial application threshold. At present, it is mainly used in aerospace high-temperature structural components, orthopedic implants and other fields [2].

2.3. Directed energy deposition(DED)

DED uses laser, electron beam, and plasma arc as heat sources to simultaneously feed metal powder/wire into the molten pool. The spatial movement of the molten pool is achieved through a multi axis motion system, forming parts by layer deposition. Its core feature is that it is not limited by the size of the enclosed forming chamber and can achieve the forming and repair of meter level large components; Can be deposited on irregular substrates [3], suitable for scenarios such as part repair, surface modification,and gradient material forming; The forming efficiency is much higher than that of powder bed technology, which can achieve rapid manufacturing of large-sized structures.

The limitations of this technology are low forming accuracy, high surface roughness, weak ability to form complex and fine structures, and it usually require subsequent machining processing. It is mainly used in the manufacturing of large-scale load-bearing components in aerospace, repair of high-end equipment parts, preparation of functionally graded materials, and other fields.

There is a clear distinction between the core characteristics and application scenarios of the three mainstream technologies. LPBF and EB-PBF are limited by powder chamber size, with maximum forming sizes usually not exceeding 800mm and 400mm [4], respectively. In terms of core advantages, LPBF excels in the forming ability of complex and fine structures, EB-PBF excels in the forming adaptability and low residual stress of high melting point and high active materials, and DED excels in forming efficiency, large-scale manufacturing capability, and part repair adaptability; In terms of core limitations, LPBF has problems with low forming efficiency and poor adaptability to high reflective materials. EB-PBF equipment has high costs and complex vacuum operation processes, while DED is difficult to achieve precise and complex structure forming.

3. Common metal materials and their applications

3.1. Titanium alloy

Titanium alloy is the most mature material system in the field of metal additive manufacturing. The forming process window is wide, and the density of additive manufacturing formed parts can reach over 99.9%. Through process control, the directional optimization of grain and texture can be achieved, and the mechanical properties can reach or even exceed the forging level.

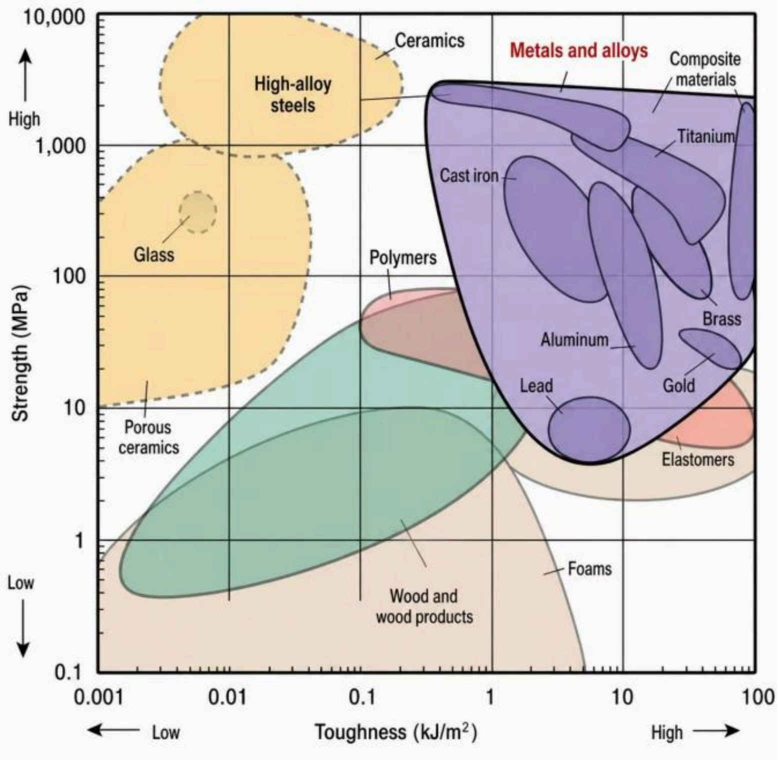

Figure 1. Comparison chart of strength toughness of different materials

Typical application scenarios can be divided into two directions: one is lightweight load-bearing structural components, engine blades, cabin structures, etc. in the aerospace field, utilizing their lightweight advantages to achieve structural weight reduction of 30% -60%; The second is artificial joints, bone implants, dental implants, etc. in the field of biomedicine, which are designed with porous biomimetic structures through additive manufacturing to reduce elastic modulus to match human bone tissue, reduce stress shielding effects, and promote bone integration.

3.2. Stainless steel

Stainless steel is the most widely used economical material in the field of additive manufacturing, with the core grade being 316L austenitic stainless steel. Its core characteristics are excellent corrosion resistance, good comprehensive mechanical properties, good welding performance, low cost, good adaptability to additive manufacturing processes, high forming stability, and it is one of the most mature material systems in the industry for process research.

The corrosion resistance of stainless steel is directly related to alloy elements. The higher the chromium content, the stronger the density and reparability of the passivation film [5]. The higher the Mo content, the better the pitting corrosion resistance of the passivation film. However, a high P content will significantly reduce the intergranular corrosion resistance of stainless steel [6]. Typical applications include automotive molds, new energy vehicle battery structural components, chemical corrosion-resistant components, medical device structural components, etc.

3.3. Aluminum alloy

Aluminum alloy has become the core material for lightweight manufacturing due to its low density, high specific strength, excellent thermal conductivity and formability. The mainstream grades for additive manufacturing are AlSi10Mg and Al Cu high-strength aluminum alloys. The core challenge lies in the high reflectivity of aluminum alloy to laser, easy oxidation, wide solidification range, and the tendency to produce defects such as pores and hot cracks. Therefore, it is necessary to improve the forming quality through process optimization and composition modification.

At present, mature additive manufacturing aluminum alloy parts have mechanical properties that can reach the level of cast aluminum alloys. The thermal conductivity of common aluminum alloys is between 120-200W/(m · k), and the higher the purity, the better the thermal conductivity. Increasing the alloy content will lead to a decrease in thermal conductivity; Its density is about 2.7g/cm^3, which is only one-third of steel. The specific strength of 7075 aluminum alloy is close to that of high-strength steel, while 6061 aluminum alloy has a more balanced comprehensive performance.

3.4. Superalloy

High temperature alloys are the core materials for aerospace hot end components, possessing excellent high-temperature strength, creep resistance, oxidation resistance, and corrosion resistance, and can serve stably for a long time above 600 ℃. The core challenge of additive manufacturing lies in the high content of alloying elements, wide solidification range, and the tendency to produce defects such as hot cracks and compositional segregation during rapid melting and solidification processes, which require extremely high compatibility between process parameters and heat treatment regimes.

By optimizing the LPBF/DED process, crack free dense forming of high-temperature alloy parts can be achieved, and precise control of microstructure and properties can be achieved through subsequent heat treatment. GH4169 alloy has excellent high-temperature performance in the range of -196-650 ℃, and can still maintain high strength, creep resistance, and oxidation resistance at 650-1000 ℃. The face centered cubic structure of its matrix, lattice strengthening effect of alloy elements, and dislocation hindrance effect of γ 'phase are the core supports of its high-temperature service performance.

Typical applications include hot end components such as aviation engine combustion chambers, turbine blades, fuel nozzles, and rocket engine nozzles, which are the core material systems for additive manufacturing of aerospace power systems.

3.5. Other special materials

Copper alloys, refractory metals (tungsten, tantalum, niobium, etc.), and metal matrix composites are currently research hotspots in the field of additive manufacturing materials. Copper alloy, with its ultra-high thermal conductivity, is mainly used in aerospace engine combustion chambers [7], radiators and other scenarios. Its tensile strength is ≥ 450MPa, yield strength is ≥ 350MPa, and it also has excellent radiation resistance and arc erosion resistance; Refractory metals have broad application prospects in the nuclear industry and high-end medical implant fields due to their high melting point, excellent high-temperature performance, and biocompatibility; Functionally graded materials can achieve continuous control of material composition through DED technology, meeting the differentiated performance requirements of different parts of components, and they are an important development direction for future material systems.

4. Process flow and quality control

4.1. Key pre-processing steps

Pre processing is the core prerequisite for determining the quality and success rate of part forming, mainly including two modules: model design and raw material preparation.

The core of model design is Design for Additive Manufacturing (DFAM), which includes topology optimization, placement angle design, and support structure design. Topology optimization is a design method that automatically generates the optimal structural layout under given design space, material usage, and load conditions. It can maximize lightweight while ensuring structural performance, and is highly compatible with the forming ability of complex structures in additive manufacturing. It is the core means of aerospace lightweight structural design.

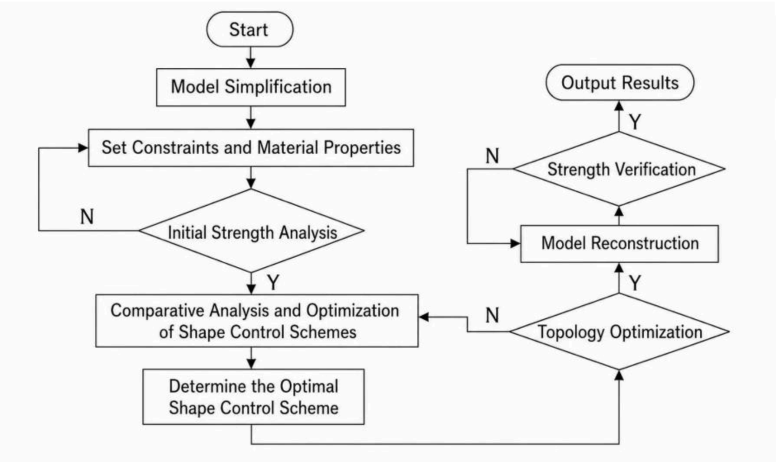

Figure 2. Topology optimization standard flowchart

Traditional machining is limited by cutting tools and molds, making it difficult to achieve complex irregular structures generated by topology optimization. However, metal additive manufacturing can directly form complex free-form surfaces, internal cavities, and other structures, perfectly solving the pain point of "easy design but difficult processing" in topology optimization. At present, topology optimization for metal additive manufacturing has formed a complete method system covering structural geometric constraints, forming constraints, and material performance constraints.

The core of raw material preparation is the quality control of metal powder. Metal powders used in additive manufacturing require strict control over core indicators such as particle size distribution, sphericity, flowability, oxygen content, and loose/compacted density. The commonly used powder particle size for LPBF process is 15-53 μ m, while the commonly used particle size for DED process is 45-150 μ m. According to the relevant provisions of GB/T46187-2025, the typical range of Hall flow rate for stainless steel powder used in additive manufacturing is 15-25s/50g, the apperant density should not be less than 3.80g/cm ^{3}, and the tap density should not be greater than 4.5g/cm ^{3}. At the same time, it is required that the powder appearance is uniform, free of lumps, and free of visible inclusions.

4.2. Process control of forming process

The core of the forming process is the precise control of process parameters, which determines the density, microstructure, and mechanical properties of the parts. The core process parameters can be divided into three categories: first, energy input parameters, including laser/electron beam power, scanning speed, scanning spacing, and layer thickness. The core parameter determines the energy input and solidification behavior of the melt pool. Taking the SLM forming process of 316L stainless steel as an example [8], the commonly used laser power is 200-400W, scanning speed is 800-1500mm/s, layer thickness is 50-200 μ m, scanning spacing is 50-150 μ m, and the ratio of the two needs to be controlled between 0.5-0.8; The layer thickness is usually controlled between 20-60 μ m. Thin layers can improve forming accuracy but reduce efficiency, while thick layers can improve efficiency but easily lead to a decrease in density. Second is the scanning strategy, including unidirectional scanning, interleaved scanning, checkerboard scanning, partitioned scanning, etc. A reasonable scanning strategy can significantly reduce thermal accumulation and residual stress, improve microstructure uniformity, and suppress deformation and cracking. Third are environmental parameters, including oxygen content, preheating temperature, chamber pressure, etc., which need to be strictly controlled according to material characteristics to avoid material oxidation and metallurgical defects.

4.3. Post processing core process

Post processing is a key step in ensuring the dimensional accuracy, surface quality, and mechanical properties of parts, and the core processes include three categories.

The first is powder cleaning, which uses high-pressure air blowing, ultrasonic cleaning and other methods to remove unmelted powder from the internal cavities and flow channels of the parts. Especially for complex porous structures, it is necessary to ensure thorough powder cleaning to avoid residual powder affecting the performance of the parts; At the same time, it is necessary to standardize the process of powder recycling and reuse, and pay attention to the impact of multiple cycles of use on the mechanical properties of the powder.

The second is heat treatment. The core heat treatment methods include stress relief annealing, solution treatment, aging treatment, etc. Among them, stress relief annealing can effectively release elastic strain energy [9], improve the dimensional stability and reliability of parts, promote the elimination of crystal defects and atomic migration, and is the most basic heat treatment process for additive manufacturing parts. Under the condition of constant holding time, increasing the annealing temperature will significantly reduce the residual stress of the parts.Solution and aging treatment can further regulate the microstructure of materials such as titanium alloys and high-temperature alloys, improving the elongation and tensile strength of the parts.

Table 2. Residual stress test data of samples under different annealing processes

Sample Number	annealing process	Residual stress in the x-direction/MPa	Residual stress in the y-direction/MPa
0	None	134.9	76.6
1	445°C×25min	79.9	59.7
2	595°C×25min	44	23
3	595°C×25min	33	16

The third is support removal and surface treatment. A strong metallurgical bond is usually formed between the supporting structure and the components, which requires precise removal of the support and supporting structure through methods such as wire cutting and mechanical processing to avoid damage to the component body. Additive manufacturing parts commonly suffer from high surface roughness defects due to the step effect of layer by layer forming, unstable melt pool, and adhesion of unmelted powder. The horizontal surface roughness of LPBF formed parts is usually 5-20 μ m, and the inclined or hanging area can reach 10-50 μ m. The commonly used surface treatment methods include mechanical polishing, sandblasting, electrochemical polishing, laser polishing, abrasive flow polishing, etc. Among them, mechanical processing can effectively improve the fatigue life and surface microhardness of parts [10]. Abrasive flow polishing can reduce the roughness of $AlSi_{10}Mg$ by more than 60% [11], and the roughness of GH4169 by more than 50%.Laser polishing can reduce the surface roughness of parts by up to 93% and increase the surface hardness of materials by 8%.

4.4. Common quality issues and control methods

Due to the process characteristics of layer by layer stacking and rapid melting, metal additive manufacturing is prone to a series of typical quality defects, which directly affect the mechanical properties, reliability, and service life of parts. The core defect types and control methods are as follows.

The first is pore defects, which are the most common internal defects in additive manufacturing. The core formation mechanism includes: insufficient energy input or unreasonable scanning strategy leading to incomplete melting of powder, forming stereolithography pores; metallurgical porosity caused by insufficient gas content and protective atmosphere in the powder. Pore defects can significantly reduce the mechanical properties of materials [12]. When the porosity is between 1% and 5%, the material strength decreases by about 10% -30%, and when the porosity exceeds 5%, the strength decreases by up to 30% -60%; For every 1% increase in porosity, the elastic modulus of the material decreases by about 2% -5%, and the fatigue strength of porous materials is usually only 30% -70% of that of dense materials. For pore defects, the core control methods include optimizing body energy density parameters and scanning strategies, strictly controlling powder quality and cavity protection atmosphere, and avoiding powder moisture and oxidation.

The second is crack defects, which are the most hidden defects that have the greatest impact on structural safety. The core formation mechanism is that under high temperature gradient and rapid cooling conditions, large residual stresses generated inside the material exceed the material's strength limit. The distance between pore defects and cracks is the most significant factor driving crack growth [13], followed by the shape and size of pores; The fracture toughness of materials containing cracks can decrease by up to 30% -50% [14], and the stress concentration factor at the crack tip can reach 5-10, which can easily cause sudden structural failure. For crack defects, the core control methods include optimizing preheating temperature and scanning strategy, reducing temperature gradient and thermal stress; at the same time, by adjusting the material composition, the solidification range of the alloy can be reduced, and the sensitivity to hot cracks can be lowered.

The third is deformation and warping.The core formation mechanism is the uneven temperature field generated by repeated heating cooling cycles in additive manufacturing, which leads to significant residual stresses. When the part separates from the substrate, the stress is redistributed and released, causing the component to warp and deform; The collapse of the molten pool and uneven heat accumulation caused by ineffective support of the suspended structure can also lead to dimensional deviations. The warpage deformation of small parts is usually 0.1-0.5mm, while the warpage deformation of large parts can reach 1-2mm or even higher. The core control methods for deformation and warping include optimizing the placement angle and support design of parts, and improving structural stiffness; using substrate preheating to reduce the temperature gradient of the melt pool and minimize thermal stress; optimize scanning strategy to reduce local heat accumulation.

The fourth is surface roughness defects. The core formation mechanism includes the step effect of layer by layer forming, adhesion of unmelted powder particles, spheroidization and powder sticking caused by unstable melt pool, and sagging of the overhanging surface melt pool. An increase in surface roughness can cause stress concentration, significantly reducing the fatigue strength and corrosion resistance of the parts. For PBF-LB/718 alloy, when the surface roughness is reduced from 14 μ m to 110nm [15], the fatigue strength of the material can be increased by 50%. The core control methods for surface roughness defects include optimizing layer thickness, laser power, and scanning strategies from the process end to reduce step effects and unmelted particles; optimize the placement angle of parts and reduce large angle overhanging surfaces.

5. Typical engineering application cases

5.1. Aerospace field

Aerospace is the most mature and high-value field for the application of metal additive manufacturing technology, centered around the three major demands of lightweight, integration, and high performance.

In the direction of lightweight load-bearing structural components, Airbus has manufactured aircraft cabin biomimetic partitions through LPBF technology. The biomimetic concept and topology optimization algorithm are used to redistribute the force path, achieving a weight reduction of 45%; in the aerospace field, topology optimization design of satellite brackets, flywheel brackets and other structures is achieved through additive manufacturing, with a weight reduction of up to 40% -70%. Among them, the satellite flywheel bracket achieves a weight reduction of 55% through topology optimization and parameter design [16], significantly reducing satellite launch costs. In the commercial aerospace field, SpaceX's SuperDraco engine uses direct metal laser sintering technology to manufacture a nickel based high-temperature alloy integral structure, which can withstand the extreme high temperature and high pressure environment of rocket engines.

In the direction of integrated functional components, GE Aviation's LEAP engine fuel nozzle is a benchmark case for additive manufacturing engineering applications. Through LPBF technology, more than 20 traditional parts are integrated into a single overall structure, reducing weight by 25%, eliminating the risk of leakage at welds and connection interfaces, and increasing service life by 5 times; NASA uses additive manufacturing technology to directly construct rocket engine combustion chambers with complex internal cooling channels, achieving integrated formation of structure and cooling system. The cooling channels can be optimized in size according to local heat loads, achieving a more uniform temperature field distribution. The efficiency of additive manufacturing heat exchangers is 13% -16% higher than traditional heat exchangers, and the efficiency can be further improved by 16% -20% after surface treatment .

In the area of large-scale component manufacturing and repair, DED technology is used to achieve the overall forming of aircraft titanium alloy large load-bearing frames, landing gear and other components, breaking through the size limitations of traditional forging and reducing assembly processes; Meanwhile, DED technology has been widely applied in the repair of high-end equipment parts such as aircraft engine blades and landing gear. After repair, the performance of the parts can reach the level of new products, significantly reducing maintenance costs and cycles. It is one of the core technologies in the field of aviation equipment maintenance.

5.2. Biomedical field

The customized and complex porous structure forming ability of metal additive manufacturing is highly matched with the personalized needs of medical implants, and is a revolutionary manufacturing technology in the field of orthopedic implants.

In the area of customized artificial joints, traditional artificial joints adopt standardized design, which is difficult to fully match the individual anatomical structure of patients, and can easily lead to stress mismatch, prosthesis loosening, and limited service life. Additive manufacturing can directly construct 3D models based on patient CT or MRI data, achieving true on-demand customization and precise replication of complex geometric shapes of patient bones. The 3D printed acetabular cup developed by Stryker have achieved commercial clinical applications. Through biomimetic porous structure design, the porosity is close to that of human trabecular bone, and the elastic modulus matches that of natural bone, effectively reducing stress shielding effect and greatly improving the long-term stability of the prosthesis. Peking University People's Hospital [17] has successfully solved the reconstruction problem of large bone defects after bone tumor surgery with a new type of titanium alloy sacral prosthesis manufactured using additive manufacturing technology.

Traditional dense metal implants have a much higher elastic modulus than human bone tissue, which can easily generate stress shielding effects, leading to degradation and absorption of surrounding bone tissue, ultimately causing prosthesis loosening. Additive manufacturing can precisely regulate the porosity, unit size, and structural morphology of porous structures, providing sufficient mechanical support at lower densities while providing channels for angiogenesis, cell migration, and nutrient transport. Research has shown [18] that diamond porous structured tantalum implants with a porosity of 80% significantly optimize the equivalent elastic modulus, significantly reduce the maximum stress, and significantly increase the proportion of area suitable for cell growth.

5.3. Automotive industry field

Metal additive manufacturing technology is driving the transformation of the automotive industry towards customization, small batch, and rapid research and development, with core applications focused on mold manufacturing, customized parts, and new energy vehicles.

In the field of conformal cooling injection molds, a large number of components in automotive manufacturing rely on injection molding or die casting, and mold cooling efficiency is the core factor affecting production cycle, dimensional accuracy, and product quality. Additive manufacturing can achieve one-time forming of complex internal flow channels, promoting the widespread application of conformal cooling channels. The cooling channels can be evenly distributed along the contour of the mold cavity, maintaining an approximately constant distance from the forming surface and achieving equidistant bonding. Experimental data shows [19] that injection molds with conformal cooling channels prepared using SLM have a 30% reduction in cooling time, a 20% reduction in production cycle, a 15% reduction in plastic part warping deformation, and a significant improvement in dimensional accuracy and surface smoothness compared to traditional linear injection molds.

In the field of customization and spare parts manufacturing, with the transformation of the automotive industry towards personalized and small batch production, the traditional large-scale manufacturing model has exposed problems such as high inventory costs, long response cycles, and difficulties in supplying spare parts for discontinued vehicle models in spare parts supply and niche parts production. Additive manufacturing, with its advantages of on-demand manufacturing, no need for molds, and fast response, has become the core solution to solve these problems. BMW has introduced additive manufacturing technology in the maintenance of classic car models, establishing a global digital inventory system that can quickly produce maintenance spare parts for discontinued models as needed, significantly reducing inventory costs and delivery cycles; Mercedes AMG extensively uses metal additive manufacturing in its powertrain and structural components, producing parts such as turbine housings and cooling manifolds to achieve weight reduction and performance improvement.

6. Technological advantages, industry challenges, and development trends

6.1. Core technological advantages

As a disruptive advanced manufacturing technology, metal additive manufacturing has four core advantages. One is the unprecedented design freedom, breaking through the geometric limitations of traditional manufacturing, which can achieve topology optimization, lattice structure, conformal flow channel, and the formation of integrated complex structures, promoting the transformation of product design from manufacturing-feasibility-oriented to performance-optimal-oriented. Structures that originally required multi part splicing and welding can be achieved through integrated manufacturing, reducing assembly errors and improving the overall strength and reliability of the structure. The second is the extremely high material utilization rate, which adopts a point by point stacking forming mode and only adds materials at the required positions. The material utilization rate can generally reach over 90%, especially for expensive materials such as titanium alloys and high-temperature alloys, which can significantly reduce raw material costs and have significant economic benefits. The third is a significant improvement in research and manufacturing efficiency, without the need for molds. After the design is completed, production can be carried out directly, and the product development cycle has been shortened from several months to several days or weeks, greatly accelerating the pace of product prototype development and design verification, and improving the response speed and innovation efficiency of enterprises to market demand. The fourth is the natural adaptability of customized production, which does not rely on molds and fixed process paths, and can flexibly adjust the design to achieve single or even small batch customized production. It has irreplaceable advantages in medical implants, aerospace customized parts, high-end equipment and other scenarios.

6.2. Current industry core challenges

The first challenge is cost control. From the perspective of equipment, the core systems of mainstream industrial grade metal additive manufacturing equipment include high-power lasers or electron beam guns, vacuum or inert gas protection systems, etc. The technical threshold of key components is high, and the manufacturing difficulty is high. The purchase cost of equipment is usually hundreds of thousands to millions of yuan. At the same time, the installation and commissioning of equipment, the matching of factory environment, and regular maintenance and calibration all bring additional cost investment, and the depreciation sharing of equipment leads to high unit part manufacturing costs. From the perspective of materials, the price of specialized spherical metal powder for additive manufacturing is much higher than that of traditional casting and forging raw materials.

The second bottleneck is the efficiency of forming. From the perspective of process principles, metal additive manufacturing mostly adopts a layer by layer stacking forming method, with each layer of powder thickness only a few tens of microns. The equipment needs to complete the cyclic process of powder spreading, point by point scanning melting, and table lowering. Even if the scanning speed is increased, it will still be constrained by factors such as melt pool stability, forming quality, and residual stress control, making it difficult to achieve a breakthrough in efficiency. In the scenario of mass production, traditional casting and forging can achieve the formation of multiple parts at once through molds, with extremely high production efficiency. However, the disadvantage of mass production efficiency in additive manufacturing is even more obvious, and it is the core bottleneck restricting its large-scale promotion in the civilian field.

The third issue is insufficient performance consistency and standardization. Additive manufacturing is a highly coupled multi physics process that involves multiple stages such as energy input, powder melting and solidification, heat conduction, and rapid cooling. Small fluctuations in process parameters, powder properties, and equipment status can cause discrepancies of the microstructure and mechanical properties of parts. At the same time, additive manufacturing parts exhibit significant mechanical anisotropy, making it difficult to meet the stringent requirements for high reliability and consistency in fields such as aerospace and nuclear power. In addition, the standard system for the entire process in the industry is still incomplete, and the standards for the entire chain from raw materials, equipment, processes to testing and acceptance are still notcomprehensive. The poor compatibility of processes between equipment from different manufacturers further restricts the large-scale engineering application of technology.

7. Conclusion

The first is large-scale and efficient. Facing the demand for large-scale components in aerospace, energy equipment and other fields, large-scale additive manufacturing equipment based on DED will continue to upgrade, expanding the forming size to the meter or even ten meter level, promoting the design concept of "overall manufacturing and reduced assembly", and simplifying the system composed of dozens or even hundreds of parts into a single component; LPBF technology will develop towards multi laser, high-power, and large format directions.

The second is intelligence and closed-loop control. Real time online monitoring of molten pool status, temperature field, splashing behavior, and defect formation is achieved based on high-precision sensing devices such as infrared thermal imagers, high-speed cameras, and photodetectors; By combining artificial intelligence and machine learning algorithms, a large amount of historical manufacturing data is used to build a mapping relationship between process parameters, microstructure, and performance. This enables dynamic adaptive adjustment of process parameters and real-time intervention of defects, constructing a closed-loop control system for the entire process, greatly improving the consistency and stability of forming quality.

The third is the diversification of material systems. Breaking through the limitations of existing commercial material systems, developing specialized aluminum alloys, high-temperature alloys, and other materials for additive manufacturing; focus on developing special material systems such as functionally graded materials and refractory metals to achieve spatially customized control of material properties ; at the same time, 4D printing technology is gradually moving from laboratory to application exploration, promoting the leap of additive manufacturing from static structural manufacturing to dynamic functional structural manufacturing.

The fourth is the integration and greening of the entire process. Promote the deep integration of additive manufacturing with traditional processes such as cutting, heat treatment, and surface treatment,develop additive and subtractive composite manufacturing technology,achieve the integration of forming and precision machining, and balance forming efficiency and dimensional accuracy. Promote the development of powder recycling and green post-treatment processes, reduce energy consumption and environmental impact throughout the entire process.

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