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Development of Laser Additive Manufacturing Technology for Metals

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Abstract: Laser additive manufacturing (LAM) technology is a key technology for realizing intelligent manufacturing in fields such as aeronautics, astronautics, and medicine. In this study, the current status and trends in LAM technology for metals in China and abroad are summarized using questionnaires, on-site surveys, and a literature review. The gap between China's technology development and the advanced international level is also analyzed and a tentative strategy for the development of LAM technology in China is proposed, with the hope of providing support to the top design of national technological and industrial strategies and for the formulation of development goals for LAM technology by 2035. Currently, research on LAM technology focuses on the active control of structural properties while ignoring the control of geometric shapes. Process monitoring of LAM equipment is highly valued for satisfying the requirements of high-quality manufacturing. Hybrid additive/subtractive manufacturing equipment has become a new research and development hotspot in order to improve the manufacturing capability and efficiency of high-value components. A sound development of the LAM industry requires an integration of the entire industrial chain, including materials, processes, equipment, tests, standards, and personnel training. China should fully explore the functions of the material genome technology to strengthen its fundamental research and improve its independent development capacity of core components and research on equipment integration. Moreover, studies of the engineering applications of LAM technology should be conducted gradually.

Keywords: laser additive manufacturing; metallic materials; equipment; industrial application; development proposals

1 Introduction

Laser additive manufacturing (LAM), in which a laser is used as the energy source, can change the traditional processing methods of metal parts thoroughly. It consists of two main methods. One is selective laser melting (SLM), which features a powder bed for laying down metal powder. Another method is laser direct metal deposition (LDMD), which is characterized by synchronous powder feeding [1]. At present, the application and development of LAM technology in the fields of aeronautics, astronautics, and medical care is the fastest [2–4]. As the manufacturing of metal parts is a major concern in related fields, an emphasis is laid on the investigation of LAM technology development for metals.

With increasing functional performance and structural complexity of metal parts, the difficulty, cost, and period of manufacture by conventional technologies, such as casting and forging, increase quickly. The LAM technology, which is both technologically advanced and compatible with a resource economy, can supply new solutions for the manufacture of high-performance and complex structures. With the help of LAM, the fabrication of topologically optimized structures, lattice structures, gradient material structures, and internally channeled structures is no longer difficult. Therefore, new structures featuring structure-function integration, weight reduction, ultrahigh strength and toughness, resistance to extreme operating conditions, or super heat dissipating ability will be produced, and the functional efficiency of structures will be increased to a large extent [1,4]. The SLM aeroengine fuel nozzle by the US General Electric Company (GE) and the LDMD aircraft frame

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made of a titanium alloy by the Beihang University are among typical cases of successful applications.

According to the development status of LAM technology for metals in China and abroad, there have only been a few real industrial applications to date. The research on basic theory, breakthroughs in key technology, degree of maturity for engineering applications, and the commercial generalization of technology developments are among the factors that restrict the industrial applications of LAM technology. At present, research in China and abroad is mainly focused on the control of properties, and foundation research, such as on porosity, cracking, microstructure characteristics, and anisotropy, has received more attention [5–9]. On the contrary, research reports related to the control of shape, the inspection of quality, and the standards for products are scarce, which also indicates that LAM of metals is not far in the transition stage from technological development to industrial application.

The current status and trends in LAM technology for metals in China and abroad are summarized in this study using questionnaires, on-site surveys, and a literature review. The gap between China and abroad, or between theory research and application requirements, is also analyzed. Related core key technologies and bottle neck technologies are suggested for the promotion of industrial applications of LAM technology.

2 Requirement analysis of metal LAM

LAM is based on the slicing of data models to achieve near net shape manufacturing of metal parts by incremental deposition, i.e., layer by layer. It is especially appropriate for the manufacturing of parts with complicated shapes, structures with gradient materials and properties, parts of composite materials, and parts of materials that are difficult to process. Therefore, it is widely favored in advanced manufacturing fields, such as the aeronautical and aerospace industries. On one hand, the relevant parts in these fields are of complex and varied shapes, and the requirements for material properties are high, which usually results in poor processability and high costs. On the other hand, to achieve complex properties, long life, high reliability, and low cost, there is an urgent need for new flight vehicles to adopt large and complicated integrated structures.

Owing to the high manufacturing precision required and the limitation in part size due to the processing chamber, SLM is commonly used to form complicated precise structures of small or medium size, and the functional attributes of SLM parts are generally greater than the load bearing attributes. To satisfy overall performance requirements, structures need to be designed creatively for many parts, such as a fuel nozzle with a complex inner oil channel, gas channel and cavity, shaft bearing seat, shell for controlling system, blade and vane in aeroengines, hatch bearings, hinges, air inlet doors, and outgas doors of cell structures in auxiliary engine rooms in aircrafts, and support in satellites. These parts are appropriate for manufacture using SLM.

Because the mechanical properties of the parts formed are good, while the shape precision is not high, LDMD is mainly used to manufacture complex load-bearing parts of medium and large sizes. Correspondingly, the load-bearing attributes of LDMD parts are greater than their functional ones. In order to improve the efficiency and function of complex structures in aeroengines, such as cases, blisks of compressors or turbines, structures with dissimilar or functional gradient materials should be adopted. To reduce weight and increase the ability of load-bearing simultaneously, parts in aircrafts, such as joints, landing gear, load-bearing frames, and load-bearing frames with cell structures for the wing or air rudder in super-speed aerobats, should be designed by topological optimization. The complexity and difficulty in manufacturing these structures yield a clear demand for LDMD technology.

In addition, for load-bearing components with special forms in aircraft or aeroengines, such as local protruding stages or tabs, it is difficult to ensure the local configuration and performance during fabrication using the forging process. Moreover, the forging equipment at present is unable to produce an ultra-sized titanium load-bearing frame that is designed for a large aircraft. Therefore, definite requirements for the development of hybrid forging/additive manufacturing and hybrid forging/additive joining technology have been raised.

3 Current development status of LAM abroad

3.1 Research progress of technology

3.1.1 SLM

Related enterprises that are capable of supplying bulk SLM powder through vacuum induction melting gas atomization, electrode induction melting gas atomization, plasma-rotating electrode process, plasma torch, and other methods have occupied the majority of the global markets [10].

Research on the LAM process has mainly focused on the active control of structural properties, and research on the relationship between microstructure, defects, performance, and process parameters of SLM technology has been conducted. Increasing the laser power and decreasing the scanning speed are beneficial for improving the density of SLM stainless steel

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components [11]. High surface roughness and porosity decrease the anti-corrosion properties of SLM $AlSi_{10}Mg$, while oxide films formed on the surface can improve the anti-corrosion properties of SLM aluminum alloy. The preheating of aluminum powder had no effect on controlling the crack perpendicular to the additive manufacturing direction during the SLM of the AW7075 specimen. Internal cracks in SLM AW7075 will lead to a much shorter fatigue life of parts when compared with similar parts manufactured by conventional manufacturing [7].

The microstructure and defects of SLM Ti-6Al-4V are mainly dependent on the energy density [5,12,13]. On one hand, a low energy density produces fine lamellar (α+β) microstructures, which easily cause porosity and lack of fusion. On the other hand, a high energy density causes acicular α' martensite and promotes the clustering of Al and the formation of α_2-Ti_3Al. The fatigue strength of deposited Ti-6Al-4V is reduced by approximately 80% compared with its wrought counterparts [6]. Hot isostatic pressing can reduce porosity and improve the properties of the material. It was found that a low energy density can reduce cracks in SLM CMSX486 single-crystal alloys, while high energy density reduces the porosity [8]. The longitudinal section of SLM CM247LC was mainly composed of columnar γ grains. The clustering of Hf, Ta, W, and Ti in SLM CM247LC increases precipitates and residual stresses and leads to internal cracking [14]. The microcracks in the SLM In738LC superalloy are related to the enrichment and segregation of Zr at the grain boundaries [15]. An appropriate amount of Re addition can refine the dendrites of the IN718 alloy, while excessive Re is detrimental to the fatigue resistance [14]. Equiaxed grains are present in SLM Hastelloy-X after heat treatment, and the yield strength decreased accordingly. The ultimate strength of the SLM Hastelloy-X can be returned to the as-deposited level after hot isostatic pressing, while the total tensile elongation until failure can be increased by 15% [16].

Research on LAM technology has been conducted carefully all over the world. It usually takes a German equipment manufacturer 6–8 months to develop SLM technology for a new type of material, for which more than 70 parameters need to be adjusted. It is an emphasis in SLM application research to realize weight reduction of structures through topological optimization, and researchers abroad have put forward some new concepts, such as design-led manufacturing and functional priority. Special support technologies have also been developed to make it possible to separate the parts from the substrate without wire electrical discharge machining, so that the pick-up cycle is shortened.

Furthermore, research and development of the LAM standard has continued with technological applications. The United States promulgated *Titanium Alloy Laser Deposited Products 6Al-4V Annealed* in 2002. Subsequently, 19 related standards, including for annealing and hot isostatic pressing, aging, stress relief annealing in the manufacturing process, and many other aspects, were issued. The formation of standards plays a role in providing foundational support for industrial applications of LAM technology.

3.1.2 LDMD

Johns Hopkins University, Pennsylvania State University, and the Mechanical Testing & Simulation System Corporation jointly developed an LDMD technology for large-scale titanium alloy parts based on a high-power CO_2 laser with a deposition rate of 1–2 kg/h in 1995 and contributed to the application of LDMD parts in aircrafts [12].

Research on LDMD mainly includes the manufacturing process and control of microstructure and properties. The mechanical properties of LDMD parts jointly prepared by the Sandia National Laboratory and the Los Alamos National Laboratory are close to or even better than those of their wrought counterparts. A repair technique for single-crystal blades through the LDMD process has been developed and applied in engineering by the École Polytechnique Fédérale de Lausanne in Switzerland based on the study of relationships between stability, precision of parts, microstructure, mechanical properties, and process parameters.

Through extensive studies on the LDMD of Ti-6Al-4V, scholars have revealed the relationship between process parameters, microstructure, and mechanical properties of additive manufacturing, and clarified the effects of process adjustment and hot isostatic pressing on the microstructure and properties [13,17–19]. LDMD technology possesses a greater degree of freedom in the control of the microstructure of materials. As expected, single-crystal and polycrystalline microstructures can be obtained by adjusting the nucleation and growth conditions of LDMD for Ni-based superalloys [9]. NASA has developed an LDMD technique for depositing multiple metal mixtures into the same microstructure to enable the performance to vary across the material parts. By integrating LAM technology with milling, German enterprises have developed a new process for fabricating components with complex shapes, which are difficult to manufacture by conventional machining and improved the accuracy and surface roughness of products [11].

3.2 Current status of equipment development

Economical and efficient LAM equipment is the basis for a wide application of LAM technology. Research on SLM equipment is mainly congregated in Germany, France, the United Kingdom, Japan, and Belgium, while research on LDMD equipment is mainly conducted in the United States and Germany.

3.2.1 Equipment for SLM

Germany started developing SLM equipment earlier than any other country. The SLM equipment developed by EOS GmbH has certain technical advantages, and some of it has been used in the manufacturing of LEAP aeroengine fuel nozzles, which were designed by GE. The quality of the products can be further improved by adding a monitoring function to the manufacturing process. Realizer GmbH developed a unique solution with an all-round design and component stacking. Equipment developed by Concept Laser GmbH has significant advantages in terms of the manufacture of large-scale components. SLM Solutions Group AG has leadership in the application of lasers and control of airflow. The specialized powder deposition system, which has become a technical barrier formed by 3D Systems, Inc of the United States, can fabricate components with precise details. Renishaw PLC of the United Kingdom is leading regarding technical characteristics in terms of the flexibility of material applications and the convenience of replacement.

3.2.2 Equipment for LDMD

EFESTO LLC of the United States has the technical advantage of manufacturing large-scale LAM metallic components. The studio size of the LDMD equipment developed by EFESTO can be up to 1500 mm× 1500 mm × 2100 mm. The LDMD equipment developed by Optomec Inc. of the United States is equipped with a 5-axis moving table and a 900 mm × 1500 mm × 900 mm studio, and the maximum forming speed can reach 1.5 kg/h. The integrated laser processing system provided by German enterprises is also mainstream LDMD equipment.

Hybrid additive/subtractive manufacturing equipment has become a global market hotspot in recent years. The LDMD device developed by DMG equipped with a 2-kW laser device and a 5-axis CNC milling machine, is 20 times faster than a conventional powder bed, and is able to mill the locations during the manufacturing process which are inaccessible in the finished parts. MAZAK Corporation of Japan has introduced equipment with the capability of 5-axis turning and milling combined machining, which can be applied to fabricating components including polygonal forgings or castings, rotational parts, and complex special-shaped parts.

3.3 Status of application

LAM of titanium alloys has been applied in aviation. A US carrier-based fighter takes the lead in using LDMD titanium alloy parts as load-bearing ones. Carpenter Technology Corporation produces advanced aviation gear using customized high-strength stainless steel through additive manufacturing. SLM corrosion-resistant supports are used in the maintenance of F-22 with a significantly decreased maintenance time. The integral frame of LDMD has been successfully applied in unmanned aerial vehicles in the UK.

SLM technology has been widely used in the manufacture of complex parts of aeroengines. GE pioneered the application of an SLM outer shell of temperature sensors for high-pressure compressors, which were approved by the US Federal Aviation Administration and have been used in more than 400 GE90-40B aeroengines. The fuel nozzles for LEAP aeroengines designed by GE are also manufactured using SLM technology and will be manufactured at a rate of 44 000 per year by 2020. The Pratt & Whitney Group produced a pipe mirror sleeve using SLM for a PW1100G-JM aeroengine. The SLM titanium alloy front bearing assembly, which contains 48 airfoil guide vanes, has been used in the Trent XWB-97 aeroengine designed by Rolls-Royce plc.

LAM technology has been applied in space vehicle manufacturing since 2012. A bending joint produced by NASA using LAM has been applied in an RS-25 rocket engine, resulting in an approximately 60% reduction in the quantity of parts, welding seams, and machining working procedures compared with conventional manufacturing. The number of parts in a hydrogen/oxygen rocket engine with integrated design and manufacturing decreased by 80%. SLM technology was used by Thales of France in fabricating TT&C antenna support elements using an aluminum alloy for the Koreasat5A and Koreasat7 communication satellites, leading to a weight reduction of 22% and a cost reduction of 30% compared with traditional processing.

The popularization and application of LAM expedites the structural topological optimization and lattice structure design of aerospace vehicles. Owing to the use of integrated manufacturing by LAM, the alumina alloy mounting bracket for the telemetry and telecontrol antenna of the Eurostar E3000 satellite platform of Astrium had an overall mass reduction by approximately 35% and an increased structural stiffness of 40%. Cobra Aero cooperates with Renishaw PLC and completes the manufacture of the integrated components of an engine with a complex lattice structure using LAM technology. Moreover, the hybrid additive/subtractive manufacturing technique has been applied. Virgin Orbit manufactured and refined parts of the combustor chamber in a rocket engine using hybrid additive/subtractive manufacturing technology and conducted engine tests 24 times in 2019.

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3.4 Experiences and implications

Based on a review of the development of LAM technology abroad, the crucial experience is that both technology research and equipment development should be guided by industrial development, and market competitiveness should be improved with the integration of industrial chains. As the principal and the biggest beneficiaries of technological development, application enterprises pay more attention to the manufacturing quality and production costs of their products. Thus, it will be much more efficient to integrate materials, processes, equipment, validation, standards, and personnel training in application enterprises in order to facilitate the development of LAM technology. GE, which has purchased manufacturing quality control companies and additive manufacturing equipment companies to strengthen the integrity of the LAM industry chain, has a leading position in LAM industry applications worldwide. The industry integration strategy mainly contributes to its leading position. Moreover, GE has more than 300 industrial manufacturing facilities worldwide. Transnational corporations pay more attention to staff training in LAM product manufacturing. GE has constructed an additive manufacturing training center with specialized equipment, where hundreds of engineers can be trained every year.

4 Development status and gap analysis of metal LAM in China

4.1 Development status

4.1.1 Metal LAM technology

Many studies have been conducted on the microstructure, defects, stress, and deformation control of LDMDs in China [11,13,14]. The Beihang University has developed key technologies such as LDMD internal defects and quality control of large titanium alloy structural parts [20]. Northwestern Polytechnical University has completed the LDMD manufacturing of superlarge titanium alloy flanges for aircrafts, with a new threshold reached in terms of forming accuracy and deformation control. Shenyang Aerospace University proposed the zonal scanning forming method, in which the deformation and cracking of parts can be effectively controlled with the LDMD process. GRIMAT Engineering Technology Research Institute Co., Ltd. has broken through the problems of TC11, TA15/Ti_2AlNb heterogeneous material interface quality control and complex shape integrated control of bladed disk and inlets, and the products have passed the test assessment.

With regards to SLM technology, research on shape and size, precise control of surface roughness, and so on, has been carried out in China. The minimum diameter of parts with inner channels processed by SLM in the Xi’an BLT Laser Forming Technology Co., Ltd. is about 0.3 mm, and the minimum wall thickness of thin-walled parts is about 0.2 mm; the overall dimensional accuracy of parts is ± 0.2 mm, and the roughness Ra is no higher than 3.2 μm. The Nanjing University of Aeronautics and Astronautics views SLM precision manufacturing as a main factor for improving the comprehensive performance of parts through process control. Xi’an Jiaotong University has applied LAM to the manufacture of hollow turbine blades, aerospace thrusters, automotive parts, etc. [11].

The AVIC Beijing Institute of Aeronautical Materials has completed comprehensive research on LAM technology. The nickel-based double-alloy turbine blisk manufactured by LDMD has passed the super rotation test examination, and the landing gears of the IL-76 aircrafts repaired by additive manufacturing have been applied in batches. An LAM ultrasonic scanning and evaluation system was developed, and the detection standard and reference block were established. The results of the evaluation and nondestructive inspection technology have been applied to the batch inspection of aircraft pulley frames, frames, and other parts to be installed on aircrafts.

In terms of powder for SLM, domestic products basically meet the requirements of the forming process. The Institute of Metals, Chinese Academy of Sciences, has broken through the threshold of clean purification preparation technology of ultrafine titanium alloy and superalloy powder for SLM, and its performance has reached the level of imported products. Titanium alloy and superalloy powder products developed by Sino-Euro Materials Technologies of Xi’an Co., Ltd. have been applied in engineering.

4.1.2 Metal LAM equipment

The domestic R&D capacity of LDMD and SLM equipment is relatively strong and consists of a certain share of market applications. Xi’an BLT Laser Forming Technology Co., Ltd. independently developed SLM series equipment and laser high-performance repair series equipment. Nanjing Zhongke Yuchen Laser Technology Co., Ltd. has developed an automatic zoom coaxial powder feeding nozzle, a long-range powder feeder, a high-efficiency inert gas circulation purification box, and other core devices, producing a series of metal LDMD equipment. In addition, Beijing Yijia 3D Technology Co., Ltd. and Beijing Xinghang Electromechanical Equipment Co., Ltd. have made good progress in the small batch production of industrial and small metal SLM equipment. Shanghai Aerospace Equipment Manufacturing Factory Co., Ltd. has made good progress in the development of standard and large-scale SLM equipment and robot LDMD equipment.

4.1.3 Application of metal LAM

LDMD is mainly used in the manufacture of load-bearing structures. The main load-bearing frame, main landing gear, and other components manufactured by the Beihang University have been applied in aerospace vehicles, gas turbine engines, and other equipment. The Shenyang Aircraft Design and Research Institute of the Aviation Industry promotes the maturity of LDMD technology through engineering application verification and realizes aircraft applications of 8 types of metal materials and 10 types of structural parts. The First Aircraft Design and Research Institute of the Aviation Industry has realized the installation and application of the outer main flap pulley frame and tail rudder arm by LDMD in a large aircraft. The Beijing Institute of Mechanical and Electrical Engineering has realized LDMD manufacturing and application of large-scale thin-walled skeleton cabin structures.

SLM is mainly used in the manufacturing of parts with complex shapes. In the field of aviation, the China Institute of Aeronautical Manufacturing Technology has realized the installation and application of SLM products, and the Chengdu Institute of Aircraft Design and Research of the Aviation Industry has used SLM air inlet doors and outgas doors with cell structures in auxiliary power rooms. The Institute of Helicopter Design and Research of the Aviation Industry has realized the installation and application of SLM parts in ventilation grille structures, rain sealing structures, inlet multi-cavity structures, etc. In the aerospace field, SLM products of the Shanghai Aerospace Equipment Manufacturing Factory Co., Ltd., such as tank discontinuous support, space radiators, and guiding devices, have been installed and applied. SLM products of Beijing Xinghang Electromechanical Equipment Co., Ltd., such as cabin structures and control surfaces, were verified by ground and flight tests. SLM of small and complex parts has been realized by the Beijing Institute of Mechanical and Electrical Engineering, and the technology maturity of the control surface, bracket, and other products reached level 5. Xinjinghe Laser Technology Development (Beijing) Co., Ltd. has applied SLM to the manufacture of large-size thin-wall titanium alloy lattice sandwich structures (heat collection window frame), which meets the strict technical requirements of deep-space exploration aircrafts.

In addition, Xi’an BLT Laser Forming Technology Co., Ltd. can provide more than 8000 SLM parts for the aerospace field every year. Huazhong University of Science and Technology has manufactured a mold of gradient material with a conformal cooling channel using combined additive/subtractive manufacturing, and molds fabricated in this manner have been widely used in the industry.

4.2 The gap being faced

4.2.1 There is a gap in the design and preparation of metal materials for LAM

The theory and method of designing specialized materials for LAM in China are still weak, and the design work of materials is limited and scattered. Materials genomics technology can shorten the R&D cycle and reduce R&D costs, and has been successfully applied in related material design abroad. In China, research on material genomics technology and its application in improving the properties of LAM specialized materials is relatively weak.

In terms of powder preparation, domestic vacuum argon atomization technology is relatively mature, and the properties of stainless steel and nickel-based alloy powder can basically meet the requirements of the forming process. However, there is a large gap in the preparation of ultrafine powders of titanium alloys and aluminum alloys. The main problems are the poor sphericity of the powder and low yield of the fine powder, which cannot meet the requirements of SLM forming; therefore, practical applications still depend on imports.

4.2.2 There is a gap between the design and manufacturing technology of metal LAM equipment

The main gap between China and other LAM technology powers, such as the United States and Germany, lies in technological equipment. SLM equipment for domestic applications is more dependent on German imports, whereas SLM equipment for large-scale engineering applications mainly depends on imports. Domestic enterprises lack self-development ability in terms of lasers, oscillating mirrors, and other core components. The processing size, stability, and processing accuracy of domestic equipment must be improved. Domestic control software for process monitoring and control of the powder flow state and molten pool state is still not perfect.

4.2.3 Lack of technological research on metal LAM

With continuous improvement in the performance of materials for turbine engines, aircrafts, and other important equipment, the processability of materials decreases. Domestic research on the LAM process of aviation backbone materials is insufficient, and effective methods such as stress deformation and cracking control have not been established. The problems of internal microstructures and defects in the parts have not been resolved, and the uniformity and batch stability of the mechanical properties of the parts are not good. Moreover, research on LAM processes of ultra-high-temperature structural materials for advanced aeroengines and high-speed aircraft is even less advanced.

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4.2.4 The dimensional accuracy and surface roughness of the product do not meet the technical requirements

Aircraft structural parts by LDMD generally have a machining allowance, and the dimensional accuracy and surface roughness are not necessarily the key constraints. However, most parts of turbine engines are of complex structures with internal flow channels and cavities. The dimension accuracy of SLM is approximately 0.1 mm, and the surface roughness Ra is approximately 6.3. However, there is still a gap between SLM and precision casting. Related products are also facing the problem of insufficient research on formation, inner surface processing, and other technologies.

4.2.5 Lack of standards and guidelines for metal LAM

At present, a common problem faced by the LAM industry in China is a lack of quality control standards, which leads to a lack of acceptance in design, material, process, inspection, microstructure and properties, dimensional accuracy, and other aspects of the products. Owing to a lack of availabtiliy of the basic data of nondestructive testing, mechanical properties, and metallurgical atlas, which are the basics of parts application, it is difficult to formulate product standards, and as a result, there are not enough guarantees for industrial applications and promotions.

5 Analysis of key technologies of LAM of metals in China

5.1 Design and manufacture of laser processing head and other core devices

The research and development of core devices under independent intellectual property rights should focus on improving the quality and performance of basic devices, such as processors, memories, industrial controllers, high-precision sensors, and digital/analog converters. The design and manufacturing of core devices and key components of process equipment should be carried out. Lasers with high-quality beams, beam shaping systems, precision optical devices, such as high-power laser scanners and dynamic focus lenses, nozzle processing heads with high precision, and other core components should be developed.

5.2 Scanning strategy, parameter planning, and online monitoring

By ensuring a breakthrough in the software technology of data design, data processing, process library, process analysis and intelligent planning, online detection and monitoring systems, adaptive intelligent control of the forming process, and a core supporting software system for LAM with independent intellectual property rights can be constructed.

5.3 Design optimization of LAM materials based on material genome

It is necessary to develop high-throughput technology models for special materials far from equilibrium conditions and to develop multi-scale simulation algorithms for high-throughput computing. Preparation technologies for powder materials with controllable composition and microstructure should be studied, and a material gene database should be established through high-throughput experiments. Through a collaboration of high-throughput computing, experiments, and databases, LAM special materials with excellent performance can be rapidly developed.

5.4 Control of properties and shape of typical structure of main material by LAM

Aiming at key materials and typical parts, the common key technologies for the control of properties and shape and the engineering applications of parts should be studied. It is necessary to master the factors affecting the final quality and solutions in the process of parts manufacturing, and form an engineering available LAM technology system, involving raw material control, process equipment, forming process, heat treatment, machining, surface treatment, non-destructive testing, and verification tests. Attention should be paid to the uniformity and batch stability of LAM parts, and the need for practical engineering applications should be met.

6 Conclusions

In order to move forward in metal LAM technology and its engineering applications, the development of LAM in China should follow the objective law of “technology–product–industry,” consolidate the technical foundation of microstructures and performance control, make up for weaknesses in the core equipment in R&D and the integration of hardware/software, strengthen product quality control, standards and verifications, and steadily promote industrial application.

(1) Lay a solid foundation for LAM research and pay attention to the technological exploration and research abilities of universities and scientific research institutes. Let industrial departments or application units take the lead in developing LAM processes and verifications of product performance. Following the principle of “easy first and difficult later” expand LAM technology gradually from conventional metals to advanced materials such as intermetallic compounds and niobium silicon

ultra-high-temperature alloys.

(2) Orderly promotion of engineering application research to achieve mass production and engineering applications as soon as possible, LAM quality control, standards, and verification work should be carried out first to achieve representative products in the aviation and aerospace fields, and then be expanded gradually to high-value products with complex structures, harsh working conditions, and poor processability, promoting their application in advanced manufacturing fields such as the nuclear industry, weapons, automobiles, and electric power equipment.

(3) Solidly carry out the research and development of product quality control and standards for LAM. The basic data of LAM, such as defect non-destructive testing, mechanical properties, metallurgical atlas, fatigue life, determination of the acceptance basis of materials, processes, non-destructive testing, microstructures and mechanical properties, dimensional accuracy, surface roughness, and formulate technical standards for LAM products in China.

(4) Combined with the actual needs of the industry, LAM-related majors in colleges and universities and vocational and technical colleges for cultivating professional and technical talents for enterprises need to be establisehd. To provide intellectual support for the development of the LAM industry, LAM training centers are set up in enterprises with technology advantages to provide special training for designers, technologists, and equipment operators in many industries in China.

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