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A Review of Metal Additive Manufacturing Application and Numerical Simulation

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A Review of Metal Additive Manufacturing Application and Numerical Simulation

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Abstract. Metal additive manufacturing has achieved high economic benefits in aerospace, military, biomedical and other high value-added industries. It has good application prospects in automobile, nuclear power, petrochemical, ship and other traditional industries. The numerical simulation can effectively predict the thermal evolution, molten pool morphology, residual stress and deformation in the process of adding metal. However, due to the limitation of the calculation speed of commercial software such as ANSYS and ABAQUS, the calculation results are difficult to accurately guide the actual manufacturing process of adding metal components. Therefore, special simulation software for additive manufacturing should be developed to carry out simulation and prediction.

1. Introduction

Additive manufacturing, also known as 3D printing, rapid prototyping and layered manufacturing, combines material processing and forming technology, computer aided design and other technologies. Based on the discrete-accumulation principle, special metal or non-metal materials are manufactured by software and control system, using sintering, melting, spraying, light curing and other methods layer by layer. The new manufacturing technology of accumulating and directly manufacturing three-dimensional solid parts is shown in Fig. 1. Compared with the traditional subtraction method of cutting raw materials, the incremental manufacturing is a kind of "bottom-up" manufacturing method through the accumulation of materials [1-2]. This makes it possible to manufacture complex structural parts, which were constrained by traditional manufacturing methods but could not be realized in the past.

ASTM defines the concept of 3D printing as: 3D printing refers to the technology of depositing materials with printing heads, nozzles or other printing technologies to produce physical objects. Therefore, 3D printing is a manufacturing method of adding materials point by point, line by line and surface by surface to form three-dimensional complex structural parts [3]. On the one hand, it can be applied to almost any type of material manufacturing; on the other hand, it will promote the development of material technology by creating a large number of new materials suitable for its unique process characteristics.
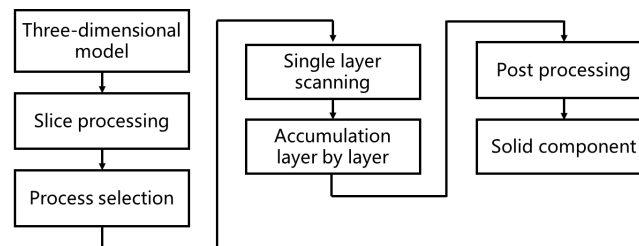
Figure 1. Process of material addition manufacturing.

According to the different materials and forming technologies used in the manufacturing of additives, the manufacturing technologies of additives can be divided into Fused Deposition Modeling (FDM), Stereo Lithography Apparatus (SLA), Laminated Object Manufacturing (LOM), Laser Stereo forming. Solid Forming (LSF), Selective Laser Melting (SLM), Electron Beam Melting (EBM), Electron Beam Freeform Fabrication (EBF), Wire-Arc Additive Manufacturing (WAAM), etc.

Thermoplastic filamentary materials such as PLA and ABS are mainly used in fused deposition forming, while slurry materials such as liquid photosensitive polymers are mainly used in photo solidification stereo forming, and sheet materials (plastic film, etc.) are mainly used in layered solid manufacturing to achieve stereo forming. The three 3D printing technologies mentioned above are mostly used in the manufacturing and forming of non-metallic materials. Metal additives manufacturing is based on metal powder (or wire) as raw materials, using laser, electron beam, arc and other high-energy beams as heat source of additives manufacturing technology. In the most widely used field of metal laser augmentation manufacturing, the laser solid forming technology (metal laser melt deposition technology) with synchronous powder feeding as its main technical feature and the laser selective melting technology with powder bed powder as its main technical feature [4-7].

Laser solid forming (LSF) is the superposition principle of rapid prototyping technology based on laser cladding. According to the processing path of layered slice information of CAD model of forming parts, high power laser is used as heat source to synchronously feed material into melting and rapid solidification, so as to realize the direct forming of metal parts [8]. As shown in Figure 2 (a). The laser power of this technology is about several kilowatts, the diameter of spot is bigger and the forming efficiency is higher. It is suitable for manufacturing large-sized metal parts, and the forming size is almost unlimited. Because of the synchronous formation of macro-structure and micro-structure, the mechanical properties can reach the level of forgings. It can realize the mixing and gradient processing of various materials, which is convenient. Controlling the mechanical properties of different parts of components; facilitating the rapid repair of large-scale damaged equipment to achieve directional tissue remanufacturing; combining with traditional manufacturing methods, it can give full play to its flexible and efficient manufacturing characteristics, and fine and complex processing of existing components.
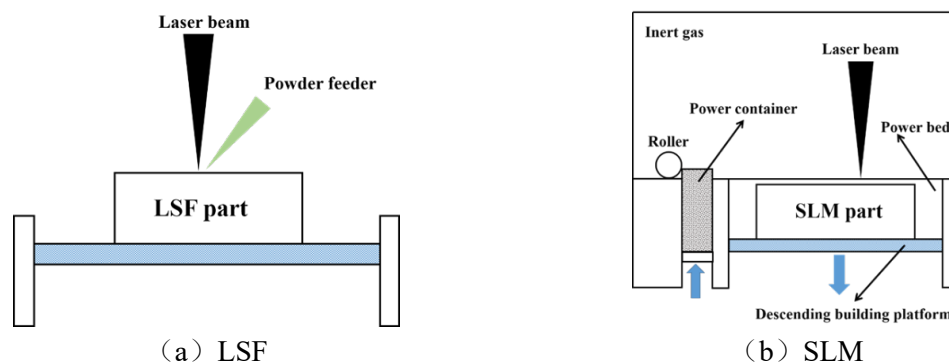

（a）LSF   （b）SLM

Figure 2. Laser Additive Manufacturing.

Selective Laser Melting (SLM) is a technology that uses high-energy laser beam to scan pre-laid metal powder according to a certain path, so that it can melt quickly, then cool and solidify rapidly, and form solid components step by step [9-10]. Its principle is shown in Figure 2 (b). This technology has high forming accuracy and can meet the requirements of use after simple processing such as grinding and sandblasting. The mechanical properties of the formed components are good, which is higher than the overall level of the castings. The forming dimension is limited by the powder laying equipment, and the maximum is not more than 500 mm. It is suitable for processing complex metal components with internal cavity. Laser power is several. About 100 watts, the facula diameter and layer thickness are smaller, and the forming efficiency is one order of magnitude lower than that of laser solid forming technology.

Compared with the traditional processing technology, the added material manufacturing technology has the following advantages [11-12]:

(1) The parts have fine grains, uniform composition and high density, rapid solidification non-equilibrium structure, and excellent comprehensive mechanical properties.

(2) Laser and other heat sources have high energy density, which can melt most metals, including Ti, Mo and other refractory, difficult-to-process, high-performance metal materials. At the same time, it can complete the forming of non-metallic materials including ceramics, plastics and other materials, and realize the diversification of processing materials.

(3) According to the working conditions and service performance requirements of the parts, by changing the chemical composition and microstructures of the forming powder and other materials, the direct forming of high-performance metal components such as multi-materials and gradient materials can be realized.

(4) Low production cost. It saves equipment, manpower and other resources. Formed components do not need Forging Industrial equipment and related supporting facilities, do not need forging blank preparation and forging die manufacturing, follow-up mechanical processing margin is small, improve the manufacturing environment, save the area. At the same time, the powder material can be reused, which improves the utilization rate of the material.

(5) Short production cycle. Additive manufacturing technology directly generates entities based on 3D modeling data, and the process of design and modification is completed in the computer, which can improve production efficiency and shorten production cycle.

(6) Processing flexibly and independently, through intelligent slice design and layered manufacturing, any complex shape structural parts can be processed theoretically, and small batch and personalized production needs can be easily fulfilled.

It is precisely in view of the unique advantages of the added material manufacturing technology that it has a wide range of application value in aerospace, military, biomedical and traditional high-end equipment manufacturing industries such as automobile, nuclear power, petrochemical, ship and so on.

2. Application of metal addition manufacturing technology

2.1. Aerospace
Metal augmentation manufacturing technology was originally and most widely used in aerospace field. First, the industry has a high demand for lightweight and uniqueness of equipment components. Second, as a core industry reflecting the state's cutting-edge manufacturing level, it has a high level of national attention and financial support.

In 1979, Snow [13] from United Technologies Corporation of America and others used synchronous powder feeding laser cladding technology to produce a radially symmetrical nickel-based superalloy turbine disk, which aroused the sensation and attention of the manufacturing industry at that time.

In the 1990s, MTS developed a flexible manufacturing technology of titanium alloy based on laser cladding deposition technology through the research of 3D printing of titanium alloy. AreoMet manufactures aircraft components such as inner keel webs, external suspension wing ribs, ribbed

panels and thrust pull beams through this technology. The National Laboratory of the United States has successively carried out three-dimensional printing research on stainless steel, titanium alloy, superalloy and other materials, and realized the formation of satellite blank parts and the repair of damaged aircraft [14].

The commercial EBM equipment was developed by the Swedish Chalmers University of Technology in 2003 through the study of electron beam selective melting forming technology. Based on this, AVIO company prepared TiAl-based alloy engine blades [15], as shown in Figure 3. In 2012, GE successfully manufactured fuel nozzles for LEAP jet engines using SLM technology. The production cycle can be shortened by 2/3, the production cost can be reduced by 50%, and the reliability has been greatly improved [16], as shown in Fig. 4.

Figure 3. Engine blade of TiAl based alloy.

Figure 4. Engine nozzle.

In recent years, GE has used SLM technology to prepare 9X series commercial aeroengine sensor shell, which has been approved by the Federal Aviation Administration of the United States [17]. It has played a great role in promoting the development of SLM technology in the aerospace field in the future.

Beijing University of Aeronautics and Astronautics, relying on the National Engineering Laboratory for the Manufacture of Additional Materials for Large Metal Components, has carried out a long-term cooperative research with the First Aircraft Design Institute and Xi'an Aircraft Industry Group Corporation. In 2005, it successfully manufactured Titanium Alloy Small and Secondary Bearing Structural Parts for Model Aircraft; in 2007, it manufactured Titanium Alloy Large. The core technology of manufacturing technology, equipment, internal quality and mechanical properties evaluation of metal laser augmentation is broken through by the type and main bearing structural parts, as shown in Fig. 5. Since then, TA15, TC4, TC11 and other aircraft reinforced frames and high-

strength aircraft landing frame components have been developed, which play an important role in the development and development of C919 large passenger aircraft.

Figure 5. Titanium alloy main bearing component.

Figure 6. The Central Wing of C919 Passenger Aircraft.

Depending on the National Laboratory of Solidification Technology, Northwest Polytechnic University mainly studies titanium alloy [19], nickel-based superalloy [20], Ti/Ni gradient material [21]. It focuses on the fabrication and repair technology of laser melt deposition additives, the control of microstructure and mechanical properties and non-destructive testing. In 2012, the upper and lower edge strips of C919 large passenger aircraft wing were manufactured by LSF technology. The size of the strips reached 450mm×350mm×3100mm. The results of flaw detection and mechanical properties test met the design requirements [22], as shown in Figure 6.

In 2013, Pratt-Whitney Rocket Dain manufactured J-2X rocket engine turbopump exhaust cap using laser selective melting forming technology, and conducted engine ignition tests at extreme temperatures and environments. Its manufacturing cost was 65% lower than that of traditional manufacturing methods. This is the first time in the world to use additives to manufacture full-size engine part [23]. In addition, the company also manufactured Saturn V F-1 rocket engine gas generator injector and MPS-120 satellite micro-propulsion system by SLM technology [24].

NASA plans to change the engine development mode from the traditional "analysis-manufacture-test" serial development mode to the "analysis-manufacture-test" parallel development mode. NASA proposes the "additive manufacturing verification engine" plan, which is expected to develop a low-cost RS-25 space engine [25] within two years, and print out GRC using SLM technology. Op-84

copper alloy thrust chamber sandwich structure and 1 mm regenerative cooling passage [26], on the basis of ensuring the internal quality of the product, reduce the residual stress, and reduce the production cycle.

Sciaky Corporation of the United States realizes rapid manufacturing of large-scale thin-walled complex structures such as titanium and titanium alloys, stainless steel, nickel-chromium alloy, tantalum, tungsten and niobium by laser direct forming technology. The size of the structures reaches 450mm × 100mm × 100mm, which improves the rapid response capability of the new generation launch vehicle and effectively realizes the "design-100 mm", Process IPT collaboration [27].

In recent years, the first Institute of Aerospace Science and technology has developed a sieve-hole swirler for a certain type of engine by means of laser selective melting equipment; the sixth Institute of Aerospace Science and technology has manufactured an engine starter and generator by SLM technology; the eighth Institute of Aerospace Science and technology has manufactured a gas valve for solid attitude and orbit control engine by adding materials; and all of them have passed the test run successfully [28].

In the future, NASA will devote itself to making the whole spacecraft with 3D printing technology, realizing the dream of self-replication of orbiting vehicles and making space telescopes from space garbage [29]. It can be seen that this technology has great research significance and development potential from the application status and application prospects of metal additives in aerospace field.

2.2. Military project

At present, the application of metal augmentation technology in the military field mainly includes the formation of complex structures and the repair of weapons and equipment [30]. The U.S. military has always attached great importance to the development of metal augmentation technology. In 2006, the U.S. Department of Defense planned to invest in additive manufacturing technology. Boeing, Loma, General Dynamics, Raytheon and other military enterprises participated in in-depth research, which greatly promoted the development and application of titanium alloy and other high alloy parts and components.

The Mobile Parts Hospital Rapid Manufacturing System developed by the U.S. Army Tank and Motor Vehicle Command uses the direct metal deposition module, which can repair the damaged and effective parts of the front battlefield in time and quickly according to the demand. At the same time, it can use the database of engineering and manufacturing data to quickly carry out metal zero. Direct manufacturing of components [31].

Since 2001, Sciaky [17] has manufactured the vertical tail, wing girder and wing box of F35 attack fighter by using EBF and traditional forging technology. The cost of parts has been reduced by about 50%. At present, Boeing Company of the United States has made more than 900 parts and components by using metal augmentation technology in a large number of UAVs and fighter aircraft.

Figure 7. Fighter components by metal additive manufacturing.

Sandia National Laboratory of the United States has manufactured three-dimensional orientation and attitude control rhenium alloy nozzles for SM3 missiles using laser cladding metal deposition technology, which can reduce the manufacturing cost and manufacturing cycle by 50%.

At present, the application of metal augmentation manufacturing technology in military industry has reached a certain scale, but it is mostly concentrated in developed countries such as Europe and the United States. The augmentation manufacturing of military weapons and equipment in China is still in its infancy.

2.3. Biological medical treatment

With the rapid development of biomedical field, the manufacturing technology of biomaterials has attracted more and more attention and research. According to the biological properties of materials, there are three kinds of manufacturing technologies for biomaterials: one is the manufacture of medical models and in vitro medical devices, mainly using the manufacturing technology of biomaterials to design and manufacture three-dimensional models or in vitro medical devices, such as three-dimensional printing of fetal models, prostheses, etc; the other is the manufacture of permanent implants, mainly using augmentation. Material manufacturing technology is used to make permanent implants, such as printing teeth or mandibles for patients; third, cell tissue printing, mainly using material-adding manufacturing technology to construct in vitro biological structures, such as kidneys, human ears, etc., but it is still in the laboratory research stage [32].

The commercial EBM equipment was developed by the Swedish Chalmers University of Technology in 2003 through the research of electron beam selective melting forming technology. Italian AVIO company based on this preparation of printed human skull, acetabular cup and so on has been applied in clinical [16].

At the same time, SLM technology also has important applications in the medical field. The University of Salamanca in Spain has successfully manufactured titanium alloy sternum and ribs using Arram SLM equipment developed by the Australian Association of Science, and successfully implanted them into patients with thoracic cancer [10], as shown in Figure 8.
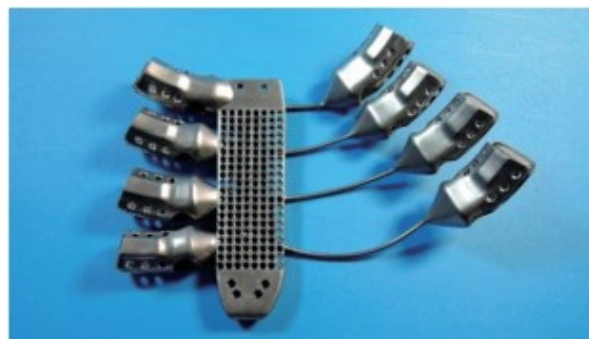

Figure 8. Titanium sternum and rib.

Figure 9. Crown by metal 3D printing.

Hanbang Technology uses SLM-100, a metal 3D printing device, to develop special dental data processing software Magics HanBang with Materialise. It can print 110 units of metal crowns at a time, as shown in Figure 9.

Hunan Huashu Hi-tech Company has used selective laser sintering technology to print out the preoperative model of fracture site by CT scanning, which makes the operation more accurate and saves more than one third of the operation time. It has had more than 2000 successful clinical cases in Changsha Xiangya Hospital and other hospitals [33].

2.4. Traditional industry

In the field of traditional equipment manufacturing, GE's oil and gas department is studying and testing the use of 3D printing technology to manufacture metal fuel nozzles for gas turbines, which is an important signal for the large-scale march of metal materials manufacturing technology into the traditional equipment manufacturing industry.

Mitsubishi Electric Machinery Co., Ltd. of Japan has formed the end blades of steam turbines by adding material manufacturing technology, and developed professional equipment which combines high-speed milling technology with laser melt deposition technology. It can produce a mould with conformal cooling channel.

Siemens also plans to use metal 3D printing technology to manufacture and repair gas turbine components, which is expected to reduce maintenance time from 10 months to one month [32]. Wuhan Binhu Mechanical and Electrical Technology Industry Co., Ltd. adopts the technology of laser selective melting and casting combined by adding materials to produce vermicular iron cylinder head of six-cylinder engine, which greatly shortens the production cycle. At the same time, the exhaust pipe and engine blade with complex internal structure are also suitable for manufacturing [34].

In the automotive industry, most automotive parts can be manufactured directly or indirectly by 3D printing. In summary, the current metal augmentation manufacturing technology mainly undertakes the design verification and function verification of new products and the production of small batches of special complex metal parts in the automotive field. Anhui Hengli Increasing Material Manufacturing Technology Co., Ltd. makes use of the combination of selective laser sintering technology and gypsum vacuum pressurized casting technology to manufacture bimetal composite engine cylinder block. It has changed the traditional casting mode of open-die and Sand-Forming mould and replaced the imported one. It has been successfully applied in Guangzhou Automobile Company and other enterprises [33].

In the marine field, metal augmentation technology has been widely used in ship aided design, hull and supporting facilities manufacturing, ship-borne UAV design and manufacturing, ship manufacturing and real-time maintenance. The U.S. Navy Surface Operations Center has developed a model of a naval ship with complex structure, which is used to simulate and test the size of wind currents on the sea surface. At the same time, the integral aluminum alloy chassis, diesel engine, intake and exhaust pipes and turbocharger housing of ship cooling device are manufactured by this technology [36].

For a long time, the repair of parts and components of traditional industrial machinery and equipment is a project that affects the normal production of enterprises and consumes human, material and financial resources. And 3D printing technology has very broad prospects for rapid repair of damaged metal parts. Kelbassa et al. [37] used 3D printing technology to repair the front wheel damping groove and casing of BR175 engine. Optomec Design has used 3D printing technology to repair wear-out parts of the T700 engine [38].

3. Numerical simulation of selective laser melting

As one of the most important means of metal laser manufacturing, selective laser melting has attracted considerable attention in recent years, and its related numerical simulation research has been thoroughly and meticulously studied by all walks of life. Because of the rapid movement of the laser heat source, the material temperature rises rapidly, and then solidifies at a very fast cooling rate. The

molten pool is formed for a very short time. At the same time, the material parameters of the material change nonlinearly and non-equilibrium with the temperature and state. Therefore, the instantaneous temperature field, stress field and melting are observed and recorded experimentally. Pool morphology is difficult, and numerical simulation is an effective way to solve this problem. Scholars at home and abroad have done a lot of simulation research on temperature field and stress field in selective laser melting process, and completed the corresponding experimental verification, and achieved a series of breakthrough theoretical results.

3.1. Research progress at home

Shi and Gu from Nanjing University of Aeronautics and Astronautics [39] established a three-dimensional finite element model of TiC/Inconel 718 composites selective laser melting of 0.56mm × 1.4mm × 0.1mm. The thermal physical parameters, latent heat of phase change and multiple heat transfer boundary of heat conduction, heat convection and heat radiation were taken into account. APDL quadratic was compiled by ANSYS. Language was developed to control the movement of the Gauss laser heat source, and life-and-death unit technology was used to control the gradual activation of the powder. The effects of process parameters on the thermal behavior and solidification mechanism of TiC/Inconel 718 selective laser melting were studied. The results show that there is a positive correlation between temperature change rate and laser power and scanning speed. The maximum temperature change rate is $7.03 \times 10^6 °C/s$. When the laser power is too low (50W) or the scanning speed is too fast (300mm/s), the maximum temperature of the molten pool is lower, the liquid phase exists too short, and the liquid phase quantity is small, the viscosity is large, which is not conducive to the spread and wetting of liquid metal in the powder gap, easy to form irregular holes and increase the porosity. Under the optimized process parameters P=100W, v=100mm/s, the remelting depth (15.1um), width (35.0um), liquid phase existence time (1.2ms), maximum temperature of molten pool (2204°C) and temperature change rate are all appropriate, which are helpful to achieve good metallurgical bonding between adjacent layers and adjacent channels.

Jiang et al. [40] of Huazhong University of Science and Technology adopted the method of material attribute transformation and unit life and death technology. The size of the calculation model was $2.4 \times 1.2 \times 2.62mm^3$. The temperature field of selective laser melting process was analyzed considering phase change and material thermal properties changing with temperature. The effects of scanning speed, laser power, lap rate and scanning mode on the temperature field were discussed. By comparing different process parameters, it is found that laser power and scanning speed are the main parameters affecting the depth of molten pool and instantaneous maximum temperature under the experimental conditions. On the basis of temperature field simulation, the influence of process parameters on thermal stress change and residual stress distribution was further analyzed by Thermo-Solid sequential coupling method. The main results show that the thermal stress fluctuates greatly with the movement of the light source, but gradually decreases with the distance of the light source. The scanning mode is the main reason that affects the evolution of the thermal stress and the distribution of the final residual stress under the experimental conditions.

Cheng [41] from Zhongbei University mainly simulated the temperature field of GH-4169 superalloy by single-pass scanning, single-layer scanning and bulk forming. The temperature distribution in the process of adding materials and the temperature change at the phase-changing junction of scanning lines were studied. The results show that the maximum instantaneous temperature increases with the decrease of scanning speed and the size of molten pool increases with the increase of laser power. The appropriate process parameters were selected and the variation law of stress field was analyzed. The results show that the stress concentration mainly occurs at the transition point between the scanning lines and the scanning lines. When the scanning is completed and cooled to room temperature, the residual stress in X direction is mainly tensile stress, which mainly concentrates on the boundary of the component. The residual stress in Y direction appears larger tensile stress at the transition point of the scanning lines, and the equivalent stress mainly concentrates on the structure. The four corners and boundary are the main causes of warpage and crack.

Jia and Lin from Northwest Polytechnic University [42] established the finite element model of transient temperature field in laser rapid prototyping process by ANSYS, and simulated the process of temperature field change in the manufacturing process of TC4 titanium alloy hollow blade. The results show that in the initial stage of hollow blade forming, the molten pool is smaller, the cooling rate is larger (-1735℃/s) and the temperature gradient is higher (about 8.34×105℃/m). The temperature gradient of the molten pool is 3.67×105℃/m, and the cooling rate of the molten pool is -438℃/s. It can be seen that with the increase of the cladding height, the molten pool is cold. However, the temperature gradient decreases as the rate decreases. After forming, the temperature of hollow blade distributes gradiently along Z axis, the temperature in the base rises slowly along Z axis, and the temperature rises quickly from the blade root to its top, which indicates that the heat transfer of the surface of the formed blade increases with the increase of the cladding height, but the overall heat dissipation direction is still from top to bottom, from the molten pool to the base.

Wang from Harbin University of Technology and others [43] established a fully parameterized finite element analysis model of temperature field of Inconel 718 Alloy selective laser melting process by combining ANSYS restart analysis technology with cyclic statements and using APDL language. The simulation results show that the heat transfer from the scanned area to the unscanned area has a preheating effect on the unscanned area. In the process of processing a layer of powder, due to the preheating effect, the maximum temperature rises with different passes of laser scanning. The preheating effect of the scanned area on the unscanned area makes the size of molten pool increase gradually with the processing. At the same time, it is clear that different process parameters such as laser power, scanning rate and scanning distance have obvious influence on the maximum temperature, maximum temperature gradient and the depth and width of the molten pool at the highest instantaneous temperature point.

Jiang et al. [44] from Zhejiang University of Technology calculated the effective thermal conductivity of 316L powders during melting. A three-dimensional transient non-linear temperature field model of 316L powders was established by ABAQUS. The size of the model was 5mm×2mm×1mm, including all powders with or without preheating entities and powders with preheating under the same processing parameters. The results of three solid powder models show that there are great differences in the temperature field transfer and morphological distribution of the three models.

Zhang et al. [45] from Dalian University of Technology used life-and-death cell technology and double ellipsoid heat source model to simulate the manufacturing process of laser augmentation, and calculated the temperature field distribution, thermal strain and thermal stress changes in the manufacturing process of laser augmentation. The results show that the manufacturing processes such as the thickness of single layer and the number of additional layers have a great influence on the overall temperature field. The larger the thickness of single layer, the less the number of additional layers, the lower the peak temperature and the smaller the change range of material temperature. The obvious tensile stress appears in the manufacturing process of laser augmentation, which may lead to the fracture of components in the manufacturing process of laser augmentation.

Deng and Yang from South China University of Technology [46] proposed a zoning scanning strategy to solve the problems of excessive accumulated residual stress, warpage and cracks in the layer caused by long scanning paths of contour offset and S-shape orthogonal in selective laser melting forming parts. Based on the numerical simulation software, S-shaped orthogonal scanning strategy and zonal scanning strategy are used to control the heat source moving path. The results show that the zonal scanning strategy can effectively reduce the boundary tension stress, reduce the fluctuation of plane residual stress and improve the mechanical properties of components.

Shen et al. [47] from Sichuan University put forward a dynamic non-linear change model of thermal conductivity of metal powder in the process of powder-solid continuous transformation, studied the changing law of transient temperature field and density field in the process of forming, discussed the relationship between material properties, process parameters and forming quality under various conditions, and provided a basis for sintering forming. The basis of parameter optimization is given.

The results show that the thermal conductivity of the substrate should be selected appropriately and it needs to be preheated. Shorter scanning line length is beneficial to improve the formability.

3.2. Research progress in foreign countries

Li et al. [48] from Nanyang Polytechnic University, Singapore, established a three-dimensional Thermo-Solid coupling model and simulated the multi-channel and multi-layer SLM process with finite element method. The model considers temperature-dependent material properties such as thermal conductivity, density, enthalpy, yield stress, thermal expansion coefficient and Young's modulus. The simulation process includes heating, melting, vaporization, solidification, shrinkage and cooling of the powder bed. The results show that the component of residual stress increases with the increase of scanning layers in the direction of layer height. At a given point, the residual stress component in the scanning direction is generally larger than the other two components, and the maximum equivalent stress occurs in the middle plane of the printed part. The temperature evolution and residual stress distribution predicted by the model can provide guidance for the optimization of SLM process parameters.

Loong-Ee et al. [49] from Nanyang Polytechnic University, Singapore, established a finite element model for selective laser melting. The model takes into account the transformation of powder to solid and effective methods for volume shrinkage and material removal. In order to determine the relationship between laser power and scanning speed and the size of melt, the melting and evaporation of powder, and the rate of temperature change, a detailed discussion was made on the change of molten pool and the rate of temperature change.

Ali et al. [50] from Kazan University, Iran, used a three-dimensional finite element model to simulate the size of molten pool during selective laser melting. The model used the characteristics of laser beam penetrating on the powder bed, and the depth depended on the powder thickness. The temperature distribution, depth, width and length of the molten pool in each channel are simulated, and the influence of different scanning speed on them is analyzed. The results show that the size of molten pool varies from the beginning to the end of track and from the first track to the next track. However, the size of the molten pool stabilizes after several tracks. After the third passage, the size of the molten pool reaches a stable state. In addition, the depth of molten pool of each track remains almost unchanged when it is about 2 mm from the starting point of the track.

Zhang et al. [51] from the Ninth University of Paris, France, developed a three-dimensional finite element model to study heat exchange during selective laser melting (SLM) of metals. This method uses a level set framework to track the size of the components to be formed, to track the interface between the printed workpiece and the unmelted powder, and between the gas domain and the continuous powder bed. In order to maintain the sustainability of computational efficiency, powder bed deposition and energy input are simplified by the proportion of the whole layer or part of each layer. The layer part is identified directly from the description of the global laser scanning plan of the component to be constructed. Each part is heated during the time interval corresponding to the exposure time of the laser beam, and then cooled during the time interval equal to the scanning time of the layer part under consideration. The global heat transfer of components manufactured by adding materials and powder materials not exposed to laser beams was simulated. In order to reduce the computational cost, a consistent grid strategy is used to refine and adapt the grid. The grid sensitivity test and energy saving verification were carried out. For the part of complex geometry, the proposed model can predict the temperature distribution and evolution of the constructed workpiece and non-melted powder in the SLM process at macro scale. Nickel-based alloys (IN718) have been applied, but numerical models can be easily extended to other materials by using their data sets.

Zhang et al. [52] from Belfort-Montberville University of Technology, France, systematically analyzed the main parameters of laser melting of 316L stainless steel powder elective zone in order to improve the mechanical properties and dimensional accuracy of manufacturing components. Firstly, the effects of process parameters such as laser beam scanning speed, laser power, substrate and powder layer thickness on the continuous melting and densification of single channel materials are

analyzed. Then, considering the influence of environmental conditions (gas properties) and preheating temperature on the density and dimensional accuracy of 316L parts, the thermal cycle and MELTING-SOLIDIFICATION mechanism are clarified by observing the microstructural characteristics of 316L parts.

Parry et al. [53] from Nottingham University, UK, used thermodynamic model to explore the effect of laser scanning on residual stress in SLM. In the two lasers scanning modes studied, complex interaction between transient thermodynamics and residual stress accumulation was observed. Residual stress was generated by the mechanism of temperature gradient, and the most important reason was the temperature gradient. The large stress component is parallel to the scanning direction, and anisotropic stress distribution will occur in the product. Different laser scanning methods have different stress distribution.

Ahmed et al. [54] from University of Exeter, UK, studied the temperature and stress fields in 316L stainless steel printed on unsupported SLM powder bed using 12.2mm×3.2mm×1mm three-dimensional finite element simulation. A non-linear transient model for Thermophysical field analysis based on sequential coupling was developed by using ANSYS parametric design language (APDL). It is found that the length of the molten pool increases with the scanning speed, while the width and depth of the molten pool decrease. The cyclic melting and cooling rate in scanning orbit results in higher Von Mises stress in the consolidation orbit of the layer.

Roberts from Woolverhampton University, UK, and R. Esterlein of Dortmund University, Germany, etc. [55] have established a 3mm×3mm×3mm finite element model to simulate the three-dimensional transient temperature field distribution in the manufacturing process of Multi-layer Laser augmentation of titanium alloy by using the cell life and death technique. The results show that the heating region of laser heat source undergoes a rapid thermal cycle, which may be related to the corresponding thermal stress cycle. The subsequent laser scanning will produce temperature peaks in the previous layer, and the temperature accumulation in the lower layer will gradually stabilize with the increase of the number of layers.

4. Conclusion

Additive manufacturing is now in the stage of rapid development. According to relevant reports, the global market value of add-on manufacturing was 8.312 billion US dollars in 2017, and the growth rate in the next five years was about 30%. From the technical point of view, the added material manufacturing can meet most of the industrial application needs. It can realize the manufacture and maintenance of metal and non-metal parts, and its performance is equivalent to or higher than that of traditional manufacturing process. From the cost point of view, the manufacturing of metal additives has achieved high economic benefits in aerospace, military, biomedical and other high value-added industries, and has a good application prospect in automobile, nuclear power, petrochemical, shipping and other traditional industries.

Selective laser melting is a fast nonequilibrium solidification process including heat transfer, mass transfer and phase transformation. The thermal evolution, molten pool morphology, residual stress and deformation can be predicted effectively by numerical simulation. Domestic and foreign scholars have made a lot of comprehensive achievements in numerical simulation of selective laser melting. The results lay a good theoretical foundation for the actual manufacturing of metal additives. However, due to the limitation of calculating speed of commercial software such as ANSYS and ABAQUS, the size of the model established by the simulation of laser augmentation manufacturing is small, and the maximum scanning forming distance is usually about several millimeters, which makes it difficult to accurately guide the actual manufacturing process of industrial metal components. Therefore, special simulation software for additive manufacturing should be developed to carry out simulation and prediction.

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