Advances and Prospects in Residual Stress Control Methods for Single-Laser and Multi-Laser Selective Laser Melting

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ABSTRACT

Selective Laser Melting (SLM) is the core technology of metal additive manufacturing, showing great potential in high-end fields such as aerospace. However, the problem of high residual stress in formed parts has always been a bottleneck restricting its development. With the rise of multi-laser collaborative printing technology, the forming efficiency of parts has been significantly improved. This paper focuses on the control methods of residual stress in single-laser and multi-laser SLM printing technologies. Firstly, it systematically reviews the research status of residual stress control in single-laser SLM printing. Then, it deeply analyzes the new challenges of residual stress control brought by multi-laser SLM printing technology. Finally, it looks forward to new strategies for multi-laser residual stress control by combining advanced technologies such as parameter coordination and path planning.

Keywords: Single Laser; Multiple Lasers; SLM Printing Technology; Residual Stress Control.

1. INTRODUCTION

Selective Laser Melting (SLM) is a metal 3D printing technology. It uses a high-power laser beam to shine on metal powder, and selectively melts the powder layer by layer, so that complex and high-precision parts can be manufactured. Because of its many advantages, SLM technology has become an important technology in aerospace, automobile and medical fields. However, in the printing process of SLM, the temperature difference between the place irradiated by laser and the surrounding area is very large, which will produce residual stress, lead to deformation and cracking of parts, and seriously affect the fatigue life and performance of parts.

At first, people who study SLM are mainly trying to optimize the working mode of a single laser. However, now the industry needs to make bigger and more things, and the traditional single laser SLM system can’t keep up and can’t meet the needs of mass production. At present, the common method to improve the forming efficiency of single laser SLM is to increase the scanning speed and the thickness of powder layer when the laser power is very high [1]. However, increasing the laser power will make the laser spot larger, which will have a bad influence on the forming accuracy and mechanical properties of the parts [2]. In contrast, multi-laser SLM technology greatly improves the manufacturing efficiency by increasing the number of lasers and making them work together, thus solving the shortage of single laser SLM. However, because of the mutual influence of thermal fields between different laser beams and the control of scanning sequence, the previous experience of controlling residual stress in traditional single laser SLM cannot be completely copied. Therefore, exploring new methods to control the residual stress in multi-laser SLM printing has become one of the most difficult problems to be solved at present.

This paper analyzes the research situation and difficulties of controlling residual stress by single-laser SLM printing technology. It points out the new challenges in residual stress control after the emergence of multi-laser SLM printing technology, and explores the new research direction of controlling residual stress in multi-laser SLM printing according to these challenges. The purpose of doing this is to provide a comprehensive reference for the research and application in this field.

2. CURRENT STATUS OF RESEARCH ON RESIDUAL STRESS CONTROL IN SINGLE-LASER SLM PRINTING

In a single laser SLM system, the moving trajectory and energy input of the laser beam are the key factors affecting the residual stress. At present, the methods to control the residual stress of single laser system mainly focus on three core directions: process parameter adjustment, scanning strategy optimization and preheating and post-processing technology, and a relatively mature residual stress control system has been formed.

2.1 Methods for Controlling Process Parameters

In SLM printing, process parameters have great influence on the microstructure and mechanical properties of parts. If the process parameters are set improperly, it is easy to affect the thermal gradient, lead to stress concentration and cause parts defects. Therefore, choosing the appropriate process parameters to reduce the stress concentration in parts has always been the research focus in the field of additive manufacturing.

Wang Jun et al. [4] developed a density prediction model of 316L stainless steel with back propagation (BP) neural network, and optimized the process parameters of the model with genetic algorithm. The results show that the relative error of the optimized model is about 0.73%, and the prediction ability is very good. The optimum technological parameters are laser power of 197.28 W, scanning speed of 623.85 mm/s, powder layer thickness of 0.1379 mm and scanning interval of 0.1139 mm. Liu Lu et al. [5] studied the influence of different process parameters on the density and residual stress of SLM printed parts. The results show that the residual tensile stress of the sample increases with the increase of laser power and the decrease of scanning speed, as shown in Figures 1 and 2. This is because the higher the laser power, the larger the molten pool will be, and the temperature will change more violently when cooling, and the thermal stress accumulation will lead to the increase of residual tensile stress. At the same time, the slow scanning speed will prolong the existence time of the molten pool, and make the heat accumulate locally, thus making the residual tensile stress more serious. Wang et al. [6] found the best range of process parameters through orthogonal experiments, and studied the principle of the influence of layer thickness and volume energy density (VED) on the shape of molten pool by using the finite element method.

At present, in the single laser SLM technology, the research on residual stress based on the regulation of process parameters is becoming more and more systematic. Many scholars are turning from the traditional parameter optimization method to digital and intelligent process parameter control, predicting stress distribution and selecting the best parameters through models.

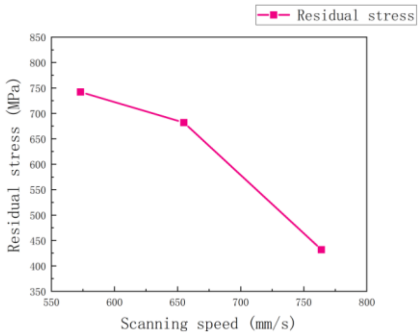

Figure 1. Residual stress values at different scanning speeds [5].

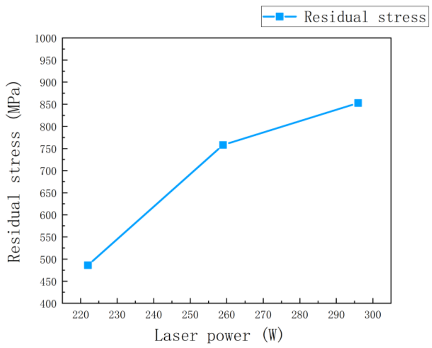

Figure 2. Residual stress values at different laser powers [5].

2.2 Methods for Optimizing Scan Strategies

The scanning strategy is mainly to change the moving route of laser beam, so as to better accumulate heat and make the force transfer more directional. Du Shihao and others [7] used a method called finite element analysis to study the influence of different scanning strategies on the temperature and stress field of a thin-walled cylinder model. The results show that a reasonable scanning strategy can effectively reduce the residual stress inside the printed part; The deformation and stress of the thin-walled cylinder printed by scanning strategy (C) are obviously improved. Ma Zhiyong and others [8] also used Refine Element Analysis to study the influence of various scanning strategies on residual stress distribution and crack defects in SLM printing, just like the schematic diagram of different scanning strategies drawn in Figure 3. The research shows that the optimized scanning strategy can effectively control the thermal-mechanical coupling behavior of parts in SLM forming process, and inhibit the occurrence of crack defects.

At present, the classical scanning strategy optimization scheme for mainstream metal materials has been gradually standardized. On the basis of the existing framework, many researchers are constantly exploring the scanning optimization strategy of complex components and special materials in single laser SLM printing through simulation and other methods.

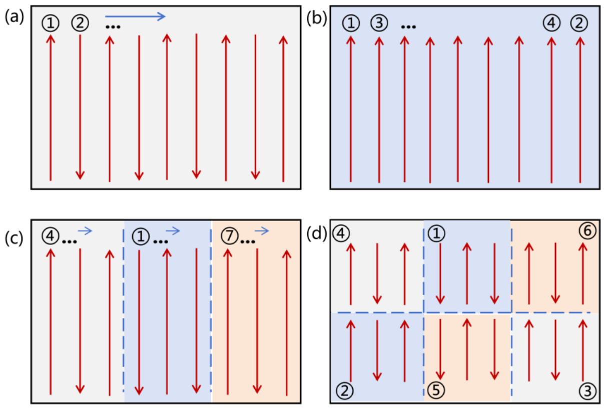

Figure 3. Schematic diagram of different scanning strategies [8].

2.3 Preheating and Post-Processing Procedures

The preheating process suppresses the thermal stress by reducing the temperature difference between the molten pool and the substrate, among which the substrate preheating is the most commonly used method; In the post-treatment process, the residual stress is released by external heating or mechanical action, so as to optimize the structural properties of the parts.

Jiang Junjie et al. [9] used finite element simulation to study the change trend of residual stress in SLM manufacturing process under different scanning paths and preheating temperatures. The results show that the preheating temperature has more obvious influence on the residual stress. When the preheating temperature of the substrate is increased from 80°C to 300°C, the residual stress is reduced by 42.7% at most. Zhang Can et al. [10] investigated the effect of substrate preheating temperature on the microstructure and mechanical properties of alloy specimens produced by SLM. The study showed that residual stress gradually decreased as the substrate preheating temperature increased.

Kumaran et al. [11] investigated changes in the mechanical properties of SLM-fabricated specimens after four different heat treatments and found that heat treatment increases the grain size of laser-formed 316L material; compared to untreated specimens, heat treatment significantly improves the ductility of the specimens. Zhang et al. [12] proposed a novel method combining SLM with ultrasonic shock treatment. Their research revealed that in-situ ultrasonic shock strengthening could reduce residual stresses during the SLM printing process from 176.3 MPa to 49.9 MPa, while also effectively reducing or even eliminating defects. Du et al. [13] found that parts printed under a static magnetic field exhibited improved ultimate tensile strength and elongation, along with enhanced alloy density.

While substrate preheating and traditional post-processing techniques for common additive manufacturing materials are already well-established, many researchers are currently focusing on exploring residual stress control methods for novel processes, such as ultrasonic shock treatment.

3. NEW CHALLENGES IN RESIDUAL STRESS CONTROL FOR MULTI-LASER SLM

While the current residual stress control system for single-laser SLM is relatively mature, its future development in high-end manufacturing is limited by low printing efficiency and prolonged heat accumulation when manufacturing large-scale parts. Multi-laser SLM printing can significantly improve printing efficiency, but issues such as the interaction of thermal fields from different laser beams and the diversity of scanning strategies mean that traditional single-laser SLM residual stress control methods are not fully applicable to multi-laser systems, presenting new challenges for residual stress control in multi-laser SLM printing.

3.1 Interaction Among Multiple Heat Sources and the Heat Accumulation Effect

In multi-laser SLM printing, the thermal fields of adjacent laser spots are easy to overlap, which leads to more obvious heat accumulation effect. The research shows that the peak interlayer temperature of multi-laser scanning is higher than that of single laser scanning, and the depth and width of molten pool will increase layer by layer, which will bring greater heat accumulation. This heat accumulation effect has a dual effect on parts. On the one hand, it prolongs the life of the molten pool and slows down the cooling speed of the surface of the parts, which can improve the distribution of residual stress [14]. On the other hand, due to the superposition of energy density, the overlapping area of thermal field is easy to form extreme temperature peak, which leads to local thermal stress exceeding yield strength, thus causing micro-defects in parts [15].

3.2 Laser Synchronization and Timing Control

The coordinated control of multiple laser heads will directly affect the continuity of that thermal-force field. Different scanning strategies will make the heat distribution on the parts different, which will make the distribution of residual stress more complicated. Experiments show that [16] printing with multiple lasers can improve the processing efficiency; However, more heat input may also lead to higher residual stress. Especially when four lasers print in one direction at the same time, overheating is inevitable, which will make the scanned area melt prematurely at high temperature, thus making the effect of residual stress more obvious. Other studies show that [17], during synchronous scanning, the alternating action of laser will instantly concentrate the heat at the seam, resulting in great residual stress; However, during sequential scanning, the high stress areas of parts are mainly concentrated on the boundaries of seam and non-seam areas.

3.3 Anisotropy and Heterogeneity in Stress Fields

The stress field in the parts made by SLM technology of a single laser is usually symmetrical around the circle. However, the stress field distribution of the parts made of SLM of multiple lasers has a great relationship with how the lasers are arranged, and the overlap of different scanning areas may affect the mechanical properties of the parts. The experiment found that [15], compared with single laser printing, the parts made of multiple laser SLM are more likely to have defects like small bubbles in the overlapping area, which has a bad influence on the tensile strength and elongation of the parts. In addition, the data also shows that [16], in the case of multiple laser scanning, the stress distribution in X, Y and Z directions is more complicated and uneven than that of single laser printing.

4. COORDINATED CONTROL STRATEGY FOR RESIDUAL STRESSES IN MULTI-LASER SLM PRINTING

Because there are several heat sources that affect each other, and it is difficult to control the switching time of the laser, the residual stress distribution in the things printed by multi-laser SLM is very uneven, different in all directions, and it will change. In this way, the previous methods to control the residual stress of single laser cannot be directly used. Next, we will focus on how the multi-laser system needs to cooperate to control the stress. We will look at it from three aspects: how to adjust printing parameters, how to design new printing paths, and how to coordinate and control multiple physical fields. By studying these latest stress control methods, we hope to find some theoretical basis for residual stress control of multi-laser SLM.

4.1 Process Parameters and Multi-Laser Co-Optimization

From the point of view of adjusting the process parameters, we can dynamically adjust the process parameters of different lasers according to the characteristics of the scanning area. For example, low energy density can be used in areas where lasers overlap to avoid overheating; While maintaining the standard energy density in the non-overlapping area to ensure the melting quality. Now, some researchers have begun to study the real-time imaging monitoring and feedback control of laser cladding process [18–20]. They use the monitoring technologies of visible light and infrared imaging to develop new monitoring systems and algorithms. At the same time, they also use closed-loop control to predict and control the defects in printing, keep the molten pool stable, and effectively manage the residual stress in parts. This research can provide a more effective solution for exploring the dynamic characteristics, process parameter optimization and manufacturing quality control of multi-laser SLM printing pool in the future.

4.2 Intelligent Path Planning and Multi-Laser Coordinated Control

Using machine learning to optimize the process parameters of SLM printing is a very popular research direction now [21–22]. By combining the finite element analysis with the prediction models of various machine learning algorithms, we can optimize the process parameters with only a small data set. However, there is little research on intelligent scanning path planning using machine learning. In the future experimental design, it may be worthwhile to try the method of machine learning: we can train the model according to the association between historical scanning path data and parts defects in small data sets in multi-laser SLM printing. Then these models can be used to predict the best scanning path and adjust it adaptively, so as to reduce the defects of parts caused by residual stress concentration. Figure 4 shows the schematic diagram of this intelligent path planning process.

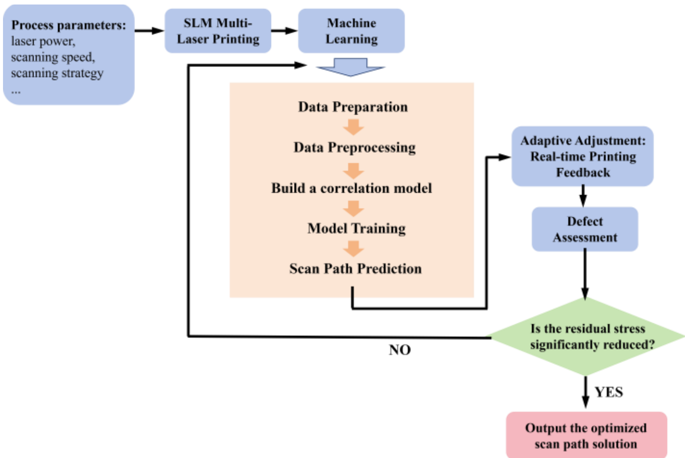

Figure 4. Schematic Diagram of the Intelligent Path Planning Process.

4.3 Multi-physics Integrated In-Situ Control Technology

Now, some scholars are studying the forming quality of parts under the influence of compound energy field [23–25]. The research shows that the use of composite energy fields (such as water-assisted laser machining, laser-electrochemical hybrid machining, and temperature/ultrasonic composite energy field machining) can improve the forming quality of parts and reduce the stress relaxation limit of parts. At the same time, in-situ monitoring technology [26–27] is used to capture light, sound, heat and other signals in real time, and then the relationship between the research object (such as part defects) and various sensor signal characteristics is established through analysis, which can provide guidance for improving the stability of laser printing process and the forming accuracy of parts. At present, there is little research on residual stress control in multi-laser SLM. Future research can explore the combination of in-situ monitoring technology under composite energy field, and open up new possibilities for the development of multi-laser SLM.

5. CONCLUSIONS AND OUTLOOK

This paper mainly talks about how to control the residual stress in the SLM manufacturing process of single-laser and multi-laser. It systematically reviews the research situation of controlling residual stress in single-laser SLM printing, deeply analyzes the new challenges encountered in controlling residual stress in multi-laser SLM, and puts forward targeted cooperative control strategies to solve the problem of residual stress in multi-laser SLM printing.

Although we have made some progress in controlling the residual stress in single laser and multi-laser SLM, there are still many problems to be solved. The core bottleneck of controlling residual stress in multi-laser system lies in the complexity of interaction between multiple heat sources, which will lead to obvious heat accumulation effect. As a result, the stress field will show anisotropy and inhomogeneity, which makes it difficult for us to effectively adjust the residual stress. At the same time, the residual stress control requires extremely high laser synchronization and timing control; Even a small deviation will have a great influence on the distribution of residual stress, and we still lack accurate theoretical guidance. The most important breakthrough is to thoroughly understand the formation mechanism of residual stress under multi-laser irradiation and the relationship between various process parameters, so as to provide a theoretical basis for subsequent control strategies. In the short term, we can conduct research in the following directions:

- An in-depth investigation on the formation mechanism of residual stress in multi-laser machining: Based on the existing research on the process parameters of single laser and the interaction characteristics of multi-laser heat sources, this study optimizes various process parameters (such as laser power, scanning speed and laser spacing) through a large number of experiments and numerical simulations, in order to reduce the influence of heat accumulation and summarize the distribution law of residual stress in multi-laser machining.
- Developing intelligent residual stress control methods: With the progress of AI and machine learning technology, there is great potential to use them in residual stress control of multi-laser SLM. By analyzing the geometric shape and material characteristics of the manufactured parts, the system can intelligently plan the scanning paths of multiple lasers. At the same time, combined with intelligent sensor technology, it can monitor the temperature field, stress field and other information in the manufacturing process in real time, so as to dynamically adjust the laser parameters and scanning path and realize closed-loop intelligent control.
- Strengthen the research and application of in-situ multi-physics field coupling control technology: Although this technology is still in its infancy, However, we should give priority to exploring some simple and effective physical field coupling methods-such as thermo-mechanical coupling and Electromagnet O-thermal coupling-to study their effects in controlling residual stress through experiments, and gradually optimize this technical route.

Generally speaking, controlling residual stress in single-laser and multi-laser SLM is a research field full of challenges and opportunities. Through continuous research and innovation, we are expected to achieve more efficient and accurate residual stress control, which will promote the application of SLM technology in aerospace, automotive manufacturing and biomedicine.

REFERENCES

[1] BREMEN S, MEINERS W, DIATLOV A. A manufacturing technology for the future[J]. Laser Technik Journal, 2012, 9 (2): 33-38.
[2] LIU B, KUAI Z Z, LI Z H, et al. Performance consistency of AlSi10Mg alloy manufactured by simulating multi laser beam selective laser melting (SLM): microstructures and mechanical properties[J]. Materials, 2018, 11(12): 2354.
[3] LI Z H, ZOU Z K, BAI P, et al. Microstructure and tensile properties of AlSi10Mg alloy manufactured by multi-laser beam selective laser melting (SLM)[J]. Metals, 2019, 9(12): 1337.
[4] Wang J, Lou G Y, Jiang R J, et al. A Prediction Model for Density in Selective Laser Melting and Optimization of Process Parameters [J]. Mechanical Design and Manufacturing, 2023, (10): 95-99+106.
[5] Liu L, Ouyang P X, Huang J, et al. Effect of Process Parameters on the Microstructure and Residual Stress of GH4169 Alloy Produced by SLM [J]. Thermal Spraying Technology, 2024, 16(02): 36-45.
[6] Wang, Z., Yue, D., Li, D. et al. Process parameter optimization and mechanical properties for selective laser melting of AlSi10Mg alloy[J]. The International Journal of Advanced Manufacturing Technology, 2024, (135): 2173-2189
[7] Du S H, Gao X Q, Liu Z, et al. Analysis of Thermal Behavior During the Forming Process of Thin-walled Cylindrical Structures Using SLM [J]. Advances in Materials, 2025, 44(11): 1035-1044.

[8] Ma Z Y, Zhang W G, Ma H F, et al. “The Effect of Scanning Strategies on Residual Stresses and Crack Defects in Fe-Ga Alloys Produced by Selective Laser Melting” [J]. Journal of Nonferrous Metals, 2026, 36(01): 223-238.
[9] Jiang J J, Wang Y B, Fan J L, et al. Effect of Scan Path and Preheating Temperature on Residual Stresses in AlSi10Mg Alloys Produced by Laser Selective Melting [J]. Special Casting and Nonferrous Alloys, 2024, 44(11): 1504-1510.
[10] Zhang C, Wang G W, Zhu J X, et al. Effect of Substrate Preheating Temperature on the Microstructure and Mechanical Properties of Selective Laser Melting AlSi9Mg1ScZr [J]. Rare Metal Materials and Engineering, 2024, 53(04): 1075-1085.
[11] Kumaran M, Senthilkumar V. Influence of heat treatment on stainless steel 316L alloy manufactured by hybrid additive manufacturing using powder bed fusion and directed energy deposition [J]. Metals and Materials International,2022,29(2):467-484.
[12] Zhang M, Liu C, Shi X, et al. Residual stress, defects and grain morphology of Ti-6Al-4V alloy produced by ultrasonic impact treatment assisted selective laser melting[J]. Applied sciences, 2016, 6(11): 304.
[13] Du D, Wang L, Dong A, et al. Promoting the densification and grain refinement with assistance of static magnetic field in laser powder bed fusion[J]. International Journal of Machine Tools and Manufacture, 2022, 183: 103965.
[14] Wu Xinxing. Finite Element Analysis of Multi-Beam Laser Melting of GH4169 Alloy [D]. Nanchang University of Aeronautics, 2023.
[15] Jing Y, Li W K Wu A Q, et al. Study on the Influence of Single- and Dual-Laser Selective Laser Melting Processes on the Ultra-High-Cycle Fatigue Behavior of AlSi10Mg Alloy [J]. Materials Reports, 2025, 39(22): 193-198.
[16] Zou Sheng. A Study on the Effects of Selective Laser Melting Processes on Residual Stresses and Warpage [D]. Wuhan University of Technology, 2024.
[17] Li R B. A Study on the Evolution of Thermal Stresses and Deformation Mechanisms in the Joining Zone of Multi-Laser Powder Bed Fusion [D]. Chongqing University, 2024.
[18] Bai Y, Dong Z X, Li Z H, et al. A Review of Visual Monitoring and Image Processing of the Melt Pool in Laser Cladding [J]. Thermal Processing Technology, 2024, 53(20): 1-8+17.
[19] Song P, He Y Y Wang F, et al. Simulation Study of the Temperature Field in the Melt Pool of 316L Stainless Steel During Laser Metal Deposition Based on Online Monitoring [J]. Aviation Science and Technology, 2025, 36(12): 59-66.
[20] Li Huaping. Research on Process Monitoring and 3D Imaging of the Laser Cladding Melt Pool Based on Visual Sensing [D]. Guangxi University, 2025.
[21] Zhang X L, Zhou Y J, Guo P C, et al. Optimization of the Selective Laser Melting Process for Al-Mg-Sc-Zr Alloys Based on Machine Learning and Numerical Simulation [J]. Journal of Nonferrous Metals, 2025, 35(02): 487-502.
[22] Yuan Zijun. A Study on the Prediction of Mechanical Properties of 316L Stainless Steel Parts Produced by Laser Powder Bed Fusion Based on Machine Learning [D]. Zhejiang University, 2023.
[23] Liu Y, Sun J J, Zhang C Y, et al. A Review of Laser–Liquid Coupled Manufacturing Technology Under the Influence of Composite Energy Fields [J]. Aviation Manufacturing Technology, 2025, 68(Z1): 73-88.
[24] Gao T J, Wen X J, Feng Z, et al. Temperature/Ultrasonic Hybrid Energy Field-Assisted Forming of Titanium Alloys and Its Applications [J]. Journal of Plasticity Engineering, 2024, 31(04): 219-226.
[25] Xu Jiahao. The Effect of Combined Thermal and Ultrasonic Energy Fields on Creep and Stress Relaxation in Ti60 Titanium Alloy [D]. Shenyang Aerospace University, 2024.
[26] Li F Y, Ke L D, Yang X, et al. Study on Elemental Burn-off and In-Situ Monitoring in Laser Powder Bed Fusion of AZ91D [J]. Applied Lasers, 2025, 45(10): 26-36.
[27] Guo Wentao. In-Situ Monitoring of the Melt Pool Characteristics During the Laser Powder Bed Fusion Process Based on Multi-Sensor Signals [D]. Wuhan Textile University, 2025.