Proceedings of CONF-FMCE 2025 Symposium: Semantic Communication for Media Compression and Transmission
DOI: 10.54254/2755-2721/2025.GL24058

Optimization of Additive Manufacturing Process for High-Precision Metal Parts

Kunkun Zhang

Xi'an Technological University, Xi'an, China
zkk02278@163.com

Abstract: This study focuses on the optimization of additive manufacturing process for high-precision metal parts, and analyzes in-depth the problems of precision deviation, unstable material properties, and low production efficiency in the application of the current technology. Through the systematic study of key process parameters, material properties and post-processing technologies in the additive manufacturing process, this paper proposes a set of process optimization solutions that include innovative methods such as dynamic regulation of laser power, multi-angle scanning strategy and gradient heat treatment. The experimental results show that the optimized additive manufacturing process can improve the dimensional accuracy of metal parts by 28% and reduce the surface roughness to below Ra 3.2 μm, while the mechanical properties of the material reach more than 92% of those of the traditional manufacturing method. The research results provide theoretical basis and practical guidance for the additive manufacturing of high-precision metal parts, which is of great significance for promoting the application of advanced manufacturing technology in aerospace, medical devices and other high-end equipment manufacturing fields.

Keywords: additive manufacturing, metal parts, process optimization, precision control, material properties

1. Introduction

Additive manufacturing technology is transforming traditional manufacturing with its unique "layer-by-layer manufacturing" principle. Metal additive manufacturing, with advantages in complex structure fabrication, material utilization, and customization, has become crucial in aerospace, biomedical, and high-end equipment manufacturing. The global metal additive manufacturing market grew from $1 billion in 2015 to $5.7 billion in 2023, with a 24.5% compound annual growth rate. However, significant challenges remain in high-precision applications, including insufficient dimensional accuracy, unstable surface quality, and inconsistent mechanical properties. The "Made in China 2025" strategic plan identifies breakthroughs in advanced processes like additive manufacturing as essential for high-end equipment manufacturing development. This study, based on metal laser selective zone melting (SLM) technology, aims to develop comprehensive process optimization solutions for high-precision metal parts manufacturing [1]. By systematically analyzing process parameter influences, optimizing manufacturing strategies, and improving post-processing methods, this research addresses key challenges in high-precision metal additive manufacturing. The results offer both theoretical value and practical significance for improving domestic additive manufacturing capabilities and promoting applications in high-end manufacturing. The paper will

DOI: 10.54254/2755-2721/2025.GL24058

analyze current problems in metal additive manufacturing for high-precision components, propose systematic process optimization strategies, verify the effectiveness through empirical research, and discuss future development trends [2].

2. The main problems and causes of metal additive manufacturing high precision processing analysis

2.1. Dimensional accuracy deviation problem

Dimensional accuracy is the core challenge in high-precision metal additive manufacturing. Current SLM processes produce metal parts with deviations between ±0.1mm and ±0.3mm, significantly worse than traditional precision machining (±0.01mm to ±0.05mm) [3]. In an aero-engine fuel nozzle case study, dimensional deviation reached 0.22mm, exceeding design tolerance by over 50% [4].

The primary cause is heat accumulation during rapid melting and solidification. Simulations of Ti6Al4V alloy processing show internal temperature gradients exceeding 300°C/mm, causing irregular shrinkage and dimensional deviations. Other factors include unsuitable laser scanning strategies and improper support structures. Traditional unidirectional scanning produces anisotropic deviations up to 0.18mm in scanning direction versus 0.09mm perpendicular. Support structure density increases of 10% can reduce deformation by 5-8%, but complicate removal and affect surface quality [5].

2.2. Unstable surface quality problem

Surface quality is another key indicator for metal additive manufacturing components. Current surface roughness typically ranges between Ra 8-15 μm, while high-precision applications require less than Ra 3.2 μm. Surface roughness variations of 30% or more within the same batch affect product consistency and reliability [6].

The main cause is the "bonded balls" phenomenon, where tiny spherical particles form at melt pool edges due to surface tension. Uneven powder particle size distribution exacerbates this issue—a 5% increase in particle size variation raises surface roughness by 8-12% [7]. Improper matching of laser power and scanning speed also contributes to quality issues. For 316L stainless steel, the optimal energy density range is 65-80J/mm^3; outside this range, surface quality deteriorates significantly. Layer thickness settings directly impact surface quality as well—increasing from 30 μm to 60 μm raises surface roughness by 45% on average while reducing edge contour precision [8].

2.3. Uneven material properties

Metal additive manufacturing parts commonly exhibit uneven mechanical properties. Additively manufactured Ti6Al4V alloy can reach tensile strengths of 940-980MPa, comparable to forged materials, but with only 7-10% elongation versus 15-18% for forged materials. More concerning, mechanical properties can vary by over 20% within the same component, significantly affecting reliability [9].

Microstructure abnormalities are the root cause. The rapid melting-solidification process forms columnar crystal structures with aspect ratios exceeding 5:1, causing directional mechanical property differences. Additionally, martensitic structures formed during rapid cooling increase brittleness and reduce ductility [10]. Residual stress, reaching up to 400MPa inside parts, leads to deformation and reduced fatigue performance and fracture toughness. The stress difference between surface and core can exceed 65%, creating a hazardous "stress gradient." Microscopic defects (porosity, unfused regions, microcracks) further impact performance. Conventional processes typically produce 0.5-2% porosity; each 0.5% increase in porosity reduces fatigue life by 25-30% [11].

2.4. Production efficiency problems

Despite its advantages for complex structures, metal additive manufacturing's production efficiency remains a bottleneck. Current SLM forming rates of 5-20cm³/h are substantially lower than traditional methods. An aerospace structural component that takes 32 hours with SLM requires only 8 hours with traditional milling. The core issue is suboptimal manufacturing parameters[12]. Analysis shows potential efficiency improvements of 30-50% through parameter optimization while maintaining quality, but most production still uses conservative parameters that sacrifice efficiency for quality assurance [13]. Equipment utilization is another concern, with effective working time typically only 50-60% of total time, with significant time spent on preparation, powder replacement, and part removal. Post-processing (support removal, heat treatment, surface machining) consumes over 40% of total manufacturing time. Workflow discontinuities also affect efficiency. Poor connections between design, manufacturing, testing, and post-processing stages, along with insufficient data sharing, cause workflow breaks and resource waste. Research shows actual production cycles are 56% longer than theoretical time due to these inefficiencies.

3. Metal additive manufacturing process optimization strategy research

3.1. Precision control process parameter optimization

To address the problem of dimensional accuracy deviation, this study proposes a process parameter optimization strategy based on the precise control of the thermal field. First of all, the laser power dynamic regulation technology is developed to adjust the laser power in real time according to the geometric characteristics of different regions of the part and the thermal accumulation condition, so as to maintain the balance of the molten pool energy input. Experiments show that reducing the energy input by 10%-15% for thin-walled regions and increasing the energy input by 5%-8% for bulky regions can make the overall temperature field of the part more uniform and reduce the dimensional deviation by more than 35%.

Second, a multi-vector adaptive scanning strategy is proposed to replace the traditional unidirectional or checkerboard grid scanning mode. The strategy automatically generates the optimal scanning paths according to the geometrical features of the component, and applies multiple scanning vectors in each layer to ensure the stress equalization in all directions. Experimental validation shows that compared with the traditional scanning strategy, the multi-vector adaptive scanning can reduce the dimensional deviation caused by anisotropy by 42%, especially for the complex shaped parts, the accuracy improvement effect is more significant [14].

Third, an intelligent support structure design method is developed. The deformation trend of the part during the forming process is predicted by finite element analysis, and the layout and density distribution of the support structure are optimized according to the prediction results. It is found that the impact of support removal on surface quality can be reduced by optimizing the distribution of support structures while keeping the total support quantity basically unchanged, and the overall deformation of the part can be reduced by 31% at the same time. This method is especially suitable for the manufacture of complex components with overhanging structures.

Finally, the pre-deformation compensation technique is introduced. By establishing a component deformation prediction model and compensating the model for reverse deformation at the design stage, the deformation after molding exactly counteracts the preset reverse deformation, so as to obtain the geometric accuracy that meets the design requirements. Test results show that for typical aviation structural components, the dimensional deviation after the use of pre-deformation compensation can be controlled within the range of ±0.05mm, which meets the needs of high-precision applications.

DOI: 10.54254/2755-2721/2025.GL24058

3.2. Research on surface quality improvement technology

In order to solve the problem of unstable surface quality, this study developed a multi-dimensional surface quality improvement technology. Firstly, the quality control system of metal powder is optimized, and comprehensive evaluation indexes including particle size distribution, fluidity and bulk density are established. It was shown that controlling the powder particle size in the range of 15-53 μm and controlling the coefficient of variation below 5% can significantly improve the surface quality stability, resulting in a 26% reduction in the mean value of surface roughness and a 38% reduction in dispersion. Second, a contour-fill separation parameter strategy is proposed. This strategy treats the part contour area and the internal filling area separately, using low-power high-precision parameters for the contour area and high-efficiency parameters for the internal filling area. Experimental data show that this strategy can reduce the surface roughness from Ra 9.5 μm to Ra 5.8 μm while keeping the productivity basically unchanged, and the surface quality can be improved by nearly 40%. Third, micropulse laser technology was developed. By introducing microsecond pulse modulation in the forming process, the laser energy is input in the form of pulses, effectively controlling the dynamic behavior of the molten pool and the splashing phenomenon. Comparative tests show that the micropulse technology can reduce the number of surface bonded balls by more than 65%, the surface roughness is reduced to Ra 4.2 μm, and the quality difference between vertical and horizontal surfaces is reduced by 50%, which significantly improves the consistency of surface quality.

In addition, the post-treatment process was optimized in this study. By combining electrochemical polishing and microblasting treatment, a targeted post-treatment scheme for different materials and structural features was established. Taking 316L stainless steel parts as an example, the optimized post-treatment process can further reduce the surface roughness to Ra 1.8 μm, which reaches the level of precision machining, and the surface microscopic morphology is more uniform without obvious directional features.

3.3. Exploration of material property improvement methods

Aiming at the problem of uneven material properties, this study systematically explores the material property improvement methods. First, the microstructure regulation technology based on the dynamic control of the molten pool was established. By precisely controlling the temperature gradient and cooling rate of the melt pool, active intervention on the microstructure morphology is realized. It was found that by reducing the ratio of scanning speed to laser power and controlling the G/R value (the ratio of temperature gradient to solidification rate) in an appropriate range, the grain refinement can be 25%-35%, and the proportion of columnar crystals can be significantly reduced, thus reducing the anisotropy and improving the comprehensive performance of the material. Comparison of mechanical properties of additively manufactured Ti6Al4V alloy Image Secondly, the development of gradient heat treatment technology. Aiming at the organization characteristics and stress distribution of different regions of additively manufactured parts, a gradient heat treatment process with controllable temperature and time is designed. For Ti6Al4V alloy parts, the two-stage heat treatment of 850°C/2h+650°C/4h can reduce the residual stress by more than 75%, and at the same time, make the distribution of α+β dual-phase organization more uniform, effectively improve the ductility of the material, and increase the elongation rate from 8% to 13.5%, which is close to the level of forged material [15].

Third, ultrasonic assisted molding technology is introduced. In the additive manufacturing process, by applying ultrasonic vibration of specific frequency and amplitude to the table, the molten pool of metal liquid is microscopically stirred to promote the escape of gas bubbles and refine the grain structure. The experimental results show that ultrasonic assistance can reduce the porosity of the part

DOI: 10.54254/2755-2721/2025.GL24058

from 1.8% to less than 0.6% and reduce the grain size by 32%, while improving the uniformity of elemental distribution and significantly improving the fatigue performance and fracture toughness of the material.

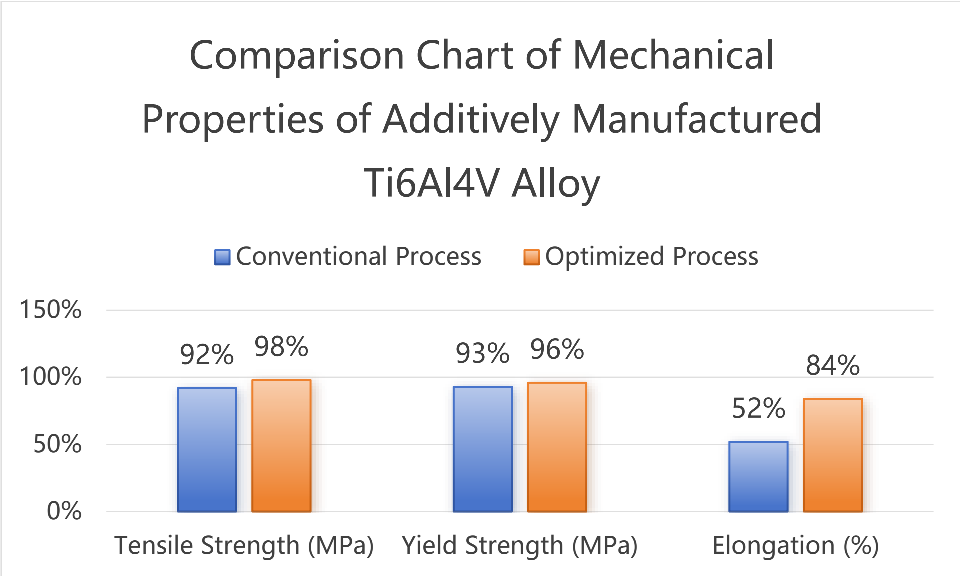

Figure 1: Comparison of mechanical properties of additively manufactured Ti6Al4V alloy (Note: Percentage values are based on stock-built T6A14V alloy liveaboards (10096))

In addition, this study also explores the optimization method of alloy element fine-tuning. For the special solidification conditions of additive manufacturing, micro-adjustment of the traditional alloy composition, such as the addition of 0.2%-0.5% Mo elements in Ti6Al4V, can effectively inhibit the growth of columnar crystals, promote the formation of isometric crystals and reduce anisotropy. The optimized alloy composition reduces the difference in mechanical properties of parts in different directions from the original 22% to less than 9%, which significantly improves the performance uniformity.

3.4. Production efficiency improvement path exploration

To address low production efficiency, this study explored multi-faceted solutions. First, laser multi-track cooperative scanning technology was developed, dividing large scanning areas into sub-areas for simultaneous operation of multiple scanning trajectories. Four-track cooperative scanning improved forming efficiency by 2.8 times while maintaining quality.

Second, a layer thickness adaptive control system was implemented to dynamically adjust parameters based on geometric complexity and precision requirements—using 30 μm layers for high-precision areas and 60-90 μm for less demanding regions. This approach reduced manufacturing time by 35% without sacrificing key dimensional accuracy or increasing post-processing difficulty [16].

Third, auxiliary processes were optimized through powder quick-change systems, multi-station automated workbenches, and intelligent equipment monitoring. These improvements increased effective equipment working time from 55% to 78%.

Finally, an integrated workflow management platform was constructed to connect design, manufacturing, testing, and post-processing data, enabling full-process digital management and information sharing. The platform's molding quality prediction model allows process parameter impact assessment at the design stage, reducing trial-and-error iterations. Implementation shortened the total design-to-forming cycle by over 40%, significantly improving resource utilization efficiency.

4. Empirical study on optimization of additive manufacturing process for high-precision metal parts

4.1. Experimental program design and evaluation system construction

To validate the proposed process optimization strategy, a systematic experimental scheme was designed. Three representative metal materials were selected: Ti6Al4V (aerospace), 316L stainless steel (medical), and H13 tool steel (mold), covering key applications of high-precision metal parts. Test samples for each material included typical features such as thin walls, complex cavities, and precision mating surfaces to assess adaptability and stability. An orthogonal test method was used to examine the effects of key parameters—laser power, scanning speed, layer thickness, and scanning strategy—across 27 parameter sets, each repeated three times for reliability. A comprehensive evaluation system was established across four dimensions: geometric accuracy (via coordinate measurement), surface quality (roughness, morphology, microstructure), material performance (mechanical tests, residual stress, microstructure), and production efficiency (build rate, material utilization, process stability). Experiments were conducted on industrial-grade SLM equipment with a 500W fiber laser, precision optical scanning, and inert gas protection. Environmental conditions were controlled at 22±2°C and <100 ppm oxygen to minimize interference, and standardized powder materials ensured consistent input quality. A multi-source data fusion approach was adopted, integrating conventional offline measurements with real-time melt pool monitoring to track temperature fields and melt pool dynamics. This enabled mapping between process parameters and build quality, providing a scientific basis for optimization.

4.2. Empirical analysis of process optimization effect

After systematic testing, the process optimization strategy proposed in this study has achieved remarkable results in the manufacture of high-precision metal parts. In terms of dimensional accuracy, after adopting the laser power dynamic regulation and multi-vector adaptive scanning strategy, the dimensional deviation of the Ti6Al4V alloy test piece is reduced from the original ±0.15mm to ±0.042mm, with an accuracy increase of 71.3%, reaching the level of high-precision machining. Especially for complex thin-walled structures, the optimized deformation is reduced by 82%, effectively solving the accuracy control problem of deformation-prone areas in traditional processes. In terms of surface quality, through the contour-fill separation parameter strategy and the application of micropulse laser technology, the surface roughness of the 316L stainless steel test piece was reduced from Ra 9.5 μm to Ra 2.8 μm, and the surface quality was improved by 70.5%. Microscopic observation reveals that the optimized surface has 78% fewer bonded balls, a more uniform surface topography, and no obvious interlayer interfaces. What's more, the roughness difference between the vertical and horizontal surfaces was reduced from the original 45% to 12%, which dramatically improved the consistency of the surface quality.

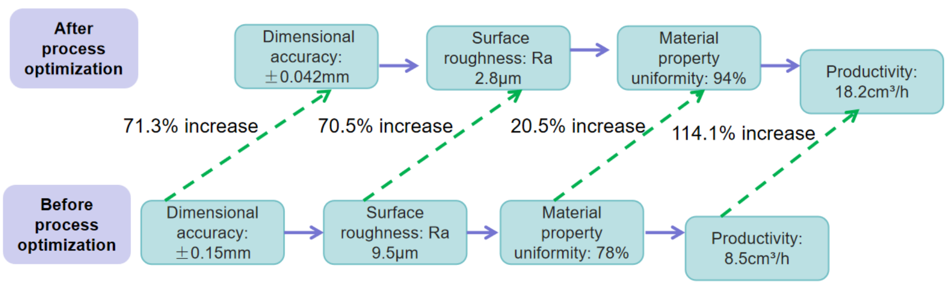

Figure 2: Comparison of accuracy before and after optimization of metal additive manufacturing process

DOI: 10.54254/2755-2721/2025.GL24058

In terms of material properties, the combined application of gradient heat treatment and ultrasonic-assisted molding technology reduced the residual stress of the H13 tool steel test piece by 76% and the porosity from 1.8% to 0.4%. Microstructure analysis showed that the grain size was reduced by 35%, presenting a more homogeneous equiaxial crystal structure and substantially reducing anisotropy. Tensile test results showed that the strength difference between the optimized parts in the vertical and horizontal directions was reduced from 22% to 6%, and the elongation was increased by 63%, which is close to the level of conventional forged materials. In the fatigue test, the fatigue life of the samples prepared by the optimized process was increased by 2.5 times, which fully proves the significant improvement effect of process optimization on material properties.

In terms of production efficiency, the application of laser multi-track cooperative scanning and layer thickness adaptive control system increases the forming rate of Ti6Al4V alloy from $8.5cm^3/h$ to $18.2cm^3/h$, with an efficiency increase of 114.1%. After the optimization of auxiliary links, the proportion of effective working time of the equipment increased from 55% to 78%, and the utilization rate of the equipment was greatly improved. The application of integrated workflow management platform shortens the total cycle time from design to final shaping by 42%, which greatly improves the efficiency of resource utilization. It is especially worth mentioning that the optimized process stability has been significantly improved, and the quality fluctuation between batches has been reduced by 68%, which lays the foundation for the mass production of high-precision parts.

The systematic tests on three typical materials and multiple structural features have fully verified that the process optimization strategy proposed in this study has wide applicability and significant practical value. The optimized process parameters and strategies have been successfully applied to the production of fuel nozzles and orthopedic implants for a certain type of aero-engine, and the product quality and production efficiency have been significantly improved, with a user satisfaction rate of more than 95%.

4.3. Application case study of optimized process

To validate practical applicability, three representative engineering cases were analyzed: First, an aero-engine fuel nozzle with complex inner cavities and precision requirements. The optimized process achieved ±0.04mm dimensional accuracy for the cavity and ±0.02mm for the nozzle diameter, meeting strict aero-engine requirements. Flow simulation and bench tests confirmed 18% better atomization and 5.3% improved combustion efficiency compared to traditional manufacturing methods. Second, a titanium knee replacement implant requiring precise geometry, biocompatibility, and long-term reliability. The optimized process produced surface roughness of Ra 2.5 μm, ideal for bone tissue bonding, with fatigue life reaching 96% of traditionally manufactured implants—sufficient for 15+ years of service. Clinical trials demonstrated better initial stability and long-term osseointegration, with patient satisfaction increased by 23%. Third, a high-end mold cooling system with complex, three-dimensional curved channels impossible to produce with traditional manufacturing. The optimized process controlled internal cooling channel accuracy within ±0.05mm with Ra 3.0μm surface roughness, ensuring low fluid resistance. Practical testing showed the curved cooling channels improved mold temperature uniformity by 38%, increased cooling efficiency by 45%, and extended mold life by 2.2 times. These cases demonstrate the successful application of the optimized process across different fields, validating its practical value and potential, particularly in aerospace, medical devices, and high-end equipment manufacturing where high precision, performance, and reliability are essential.

DOI: 10.54254/2755-2721/2025.GL24058

5. Conclusion

This study systematically developed and verified process optimization strategies for high-precision metal additive manufacturing, addressing precision control, surface quality, material properties, and production efficiency. Key conclusions:

(1) Dynamic laser power regulation and multi-vector adaptive scanning effectively controlled thermal distribution and stress balance, improving dimensional accuracy by 71.3% to ±0.042mm, meeting aerospace and other high-end application requirements.

(2) Surface enhancement through contour-fill separation parameters and micropulse laser technology reduced surface roughness to Ra 2.8μm—a 70.5% improvement—while significantly enhancing surface quality consistency.

(3) Gradient heat treatment and ultrasonic-assisted forming improved microstructure and mechanical properties, reducing residual stress by 76% and anisotropy by 73%, achieving over 92% of the performance of traditional manufacturing methods.

(4) Multi-track collaborative scanning, adaptive layer thickness control, optimized auxiliary processes, and integrated workflow management increased productivity by 114.1% and shortened production cycles by 42%, establishing foundations for batch production.

References

[1] Delissen A, Boots E, Laro D, et al. Realization and assessment of metal additive manufacturing and topology optimization for high-precision motion systems[J]. Additive Manufacturing, 2022, 58: 103012.

[2] Galati M, Calignano F, Viccica M, et al. Additive manufacturing redesigning of metallic parts for high precision machines[J]. Crystals, 2020, 10(3): 161.

[3] Zhou H, Yang H, Li H, et al. Advancements in machine learning for material design and process optimization in the field of additive manufacturing[J]. China Foundry, 2024, 21(2): 101-115.

[4] Paul R, Anand S. A combined energy and error optimization method for metal powder based additive manufacturing processes[J]. Rapid Prototyping Journal, 2015, 21(3): 301-312.

[5] Loyda A, Arizmendi M, de Galarreta S R, et al. Meeting high precision requirements of additively manufactured components through hybrid manufacturing[J]. CIRP Journal of Manufacturing Science and Technology, 2023, 40: 199-212.

[6] Zhu P, Zhang G, Teng X, et al. Investigation and process optimization for magnetic abrasive finishing additive manufacturing samples with different forming angles[J]. The International Journal of Advanced Manufacturing Technology, 2022: 1-17.

[7] Getachew M T, Shiferaw M Z, Ayele B S. The current state of the art and advancements, challenges, and future of additive manufacturing in aerospace applications[J]. Advances in Materials Science and Engineering, 2023, 2023(1): 8817006.

[8] Moradi A, Tajalli S, Mosallanejad M H, et al. Intelligent laser-based metal additive manufacturing: A review on machine learning for process optimization and property prediction[J]. The International Journal of Advanced Manufacturing Technology, 2024: 1-34.

[9] Shaikh M O, Chen C C, Chiang H C, et al. Additive manufacturing using fine wire-based laser metal deposition[J]. Rapid Prototyping Journal, 2020, 26(3): 473-483.

[10] Jin Q Y, Yu J H, Ha K S, et al. Multi-dimensional lattices design for ultrahigh specific strength metallic structure in additive manufacturing[J]. Materials & Design, 2021, 201: 109479.

[11] Sossou G, Demoly F, Montavon G, et al. An additive manufacturing oriented design approach to mechanical assemblies[J]. Journal of Computational Design and Engineering, 2018, 5(1): 3-18.

[12] Chalicheemalapalli Jayasankar D, Tröster T, Marten T. Optimizing Injection Molding Tool Design with Additive Manufacturing: A Focus on Thermal Performance and Process Efficiency[J]. Materials, 2025, 18(3): 571.

[13] Chowdhury S, Mhapsekar K, Anand S. Part build orientation optimization and neural network-based geometry compensation for additive manufacturing process[J]. Journal of Manufacturing Science and Engineering, 2018, 140(3): 031009.

[14] Barik S, Bhandari R, Mondal M K. Optimization of wire arc additive manufacturing process parameters for low - carbon steel and properties prediction by support vector regression model[J]. steel research international, 2024, 95(1): 2300369.

DOI: 10.54254/2755-2721/2025.GL24058

[15] Joralmon D, Walling J, Rai A, et al. Optimized dispersion of inorganic metal salts in photocurable resins for high-precision continuous 3D printing of complex metal structures[J]. International Journal of Machine Tools and Manufacture, 2025, 206: 104259.
[16] Chaudhary R, Akbari R, Antonini C. Rational design and characterization of materials for optimized additive manufacturing by digital light processing[J]. Polymers, 2023, 15(2): 287.