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The Application of Laser Forming Technology in Additive Manufacturing and Its Quality Monitoring

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Abstract: This paper conducts an in-depth investigation into the field of Selective Laser Melting (SLM) within additive manufacturing (AM) technology, providing a detailed analysis of its market background, current status, and development prospects. As a revolutionary pioneer in future manufacturing, AM technology has rapidly emerged in recent years and found widespread application in high-end manufacturing sectors such as scientific research, healthcare, military industry, aerospace, and aviation. SLM technology, as a critical branch of AM, has become a focal point in numerous fields due to its advantages of high precision, high efficiency, and material diversity. This paper first outlines the industry background of AM technology, including its development history, primary methods, and technical characteristics. Subsequently, by comparatively analyzing the key technical parameters of major domestic and international SLM printing equipment brands, the current market status of SLM technology is revealed. In the competitor analysis, the paper focuses on the latest advancements in melt pool temperature monitoring technology and powder spreading detection technology. It points out the limitations of traditional temperature measurement techniques in aspects such as single-point measurement, accuracy, and response speed. The innovative approaches adopted in this project — namely, photoelectric sensor-fused thermal imaging processing technology and artificial intelligence (AI)-based machine vision inspection methods—are introduced. Furthermore, the paper explores future development trends for SLM technology, including product line expansion, service upgrades, and the positive impact of policy support and industry development. Through the research conducted in this project, we deeply appreciate the critical importance of technological innovation for enhancing the forming success rate of SLM technology and reducing material and energy costs.

Keywords: Additive manufacturing, Selective Laser Melting , Process control, Melt pool temperature monitoring

1. Introduction

Additive manufacturing (AM), widely acclaimed as a revolutionary pioneer in future manufacturing and also known as 3D printing technology, has emerged rapidly in recent years as a novel manufacturing approach. It integrates advanced manufacturing, intelligent manufacturing, green manufacturing, new material development, and precision control technologies, demonstrating remarkable innovative vitality in the manufacturing sector. Currently, AM technology has spawned numerous widely adopted methods, including Fused Deposition Modeling (FDM), Stereolithography (SLA), Selective Laser Melting (SLM), and Selective Laser Sintering (SLS). Each technique possesses distinct characteristics, providing diverse and flexible solutions for manufacturing requirements across various fields.

The rapid emergence and widespread adoption of additive manufacturing (AM) technology in high-end sectors such as scientific research, healthcare, military industry, aerospace, and aviation in recent years primarily stem from its significant advantages over traditional subtractive manufacturing. These advantages include efficient production workflows, minimal manufacturing constraints, and highly intelligent operational characteristics. It is precisely these benefits that have garnered extensive global attention for AM technology and driven continuous expansion of its industry revenue scale.

2. Object and subject of research

According to the Wohlers Report, the global 3D printing (additive manufacturing) market reached USD 18 billion in 2022, representing an 18.1% year-on-year growth. The compound annual growth rate (CAGR) from 2016 to 2022 stood at 14.7%. The global market is projected to expand to USD 29.8 billion by 2025 (18.3% CAGR for 2022–2025), with further growth anticipated to reach USD 85.3 billion by 2030 (23.4% CAGR for 2025–2030). In the Chinese market, the China Additive Manufacturing Industry Development Research Report released by the China Additive Manufacturing Industry Alliance indicates sustained expansion of the domestic AM industry scale over the past four years. Notably, industrial-grade AM equipment accounted for 55% of total sales in China’ s market during 2021, demonstrating the nation’ s robust capabilities and promising prospects in this sector.

Table2-1 The scale of China's additive manufacturing industry

Time	2017	2018	2019	2020	2021	2022	2023	2024
Scale	96	120	158	195	262	330	410	500

Concurrently, the development prospects of the additive manufacturing (AM) industry appear equally promising. According to projections from authoritative research reports such as the Wohlers Report and the China Additive Manufacturing Industry Development Research Report, China's AM industry is expected to maintain a minimum compound annual growth rate (CAGR) of 25.21%, compared to the global projection exceeding 30%. These remarkable growth indicators not only reveal the substantial market potential and expansive development trajectory of the AM industry, but also signify its emergence as a key engine for driving sustained global economic growth.

3. Market research

In metal additive manufacturing (AM), Selective Laser Melting (SLM) stands as one of the most representative and intensively researched processes, and also ranks among the most commercially scaled AM technologies. SLM enables the monolithic fabrication of components with complex internal structures unattainable through conventional manufacturing techniques.

Table3-1 Current metal 3D printing enterprises

Establish	Name	Country	Primary technology	Yearly income(USD)	Remark
1989	3DSystems	American	SLM/SLS	557 million	-
1905	EOS	German	SLM/SLS	-	-
2002	Concept Laser	German	SLM	-	Acquired by GE
2010	SLM	German	SLM	-	-

	Solutions				
2004	Shining 3D	China	SLM/SLS	66.96 million	-
2011	Bright Laser	China	SLM/SLS	5.98 million	-
2009	Farsoon	China	SLM	5.73 million	-

In metal additive manufacturing (AM), Selective Laser Melting (SLM) stands as one of the most representative and intensively researched processes, and also ranks among the most commercially scaled AM technologies. SLM enables the monolithic fabrication of components with complex internal structures unattainable through conventional manufacturing techniques.

Despite substantial advancements in metal AM, process standardization remains challenging, particularly regarding yield assurance for large-scale components. Significant deviations in mechanical properties and geometric accuracy may occur even when identical equipment processes identical parts. This variability stems primarily from the predominant use of open-loop or semi-closed-loop control in current metal AM processes, coupled with inadequate monitoring technologies for intermediate stages such as melt pool temperature, powder spreading quality, and layer-wise formation. Consequently, existing AM systems lack efficient integration of intelligent trajectory tracking, real-time defect recognition, adaptive feedback, and dynamic process adjustment. Implementing comprehensive closed-loop monitoring could substantially enhance part success rates and reduce production costs for enterprises.

Concurrently, China has increasingly prioritized the development of in-process monitoring technologies for metal AM. Multiple governmental bodies including the Ministry of Industry and Information Technology (MIIT) have introduced supportive policies:The Ministry of Science and Technology's 2022 Annual Project Application Guide for the National Key R&D Program "Additive Manufacturing and Laser Manufacturing" (March 2022) specifically emphasizes developing online monitoring and quality evaluation technologies for laser powder bed fusion, including efficient in-situ quality assessment, feature recognition, and parameter control methods.Made in China 2025 explicitly identifies AM as a key domain for advancing intelligent manufacturing equipment, smart production processes, and breakthrough technology development.MIIT's Notice on Declaring 2018 Industrial Technology Foundation Public Service Capability Improvement and Industry Quality Common Technology Promotion Projects (August 2018) proposed subsidies up to ¥3 million per qualified entity for quality control and evaluation of metal 3D printing powders and components.

Thus, advancing SLM melt pool temperature monitoring and online powder spreading detection technologies directly aligns with national AM development strategies and satisfies MIIT's criteria for specialized, sophisticated, distinctive, and innovative "Little Giant" enterprises, indicating substantial growth potential.

4. Research and analysis

In the domain of Selective Laser Melting (SLM) printing equipment, Wohlers Report 2021 authoritatively indicates that four Chinese brands featured prominently among the top ten global SLM equipment manufacturers by sales volume in 2020, demonstrating China's formidable competitiveness in this sector. Specifically, China's Farsoon (3rd), Guangdong Hanbang Laser Technology (4th), Eplus3D (5th), and Bright Laser Technologies (BLT, 7th) secured these rankings, showcasing their exceptional market performance and technological prowess.

Among international manufacturers, Germany's EOS maintained its leading position through technological superiority and brand influence, followed by US-based GE Additive in second place. Furthermore, Germany's

TRUMPF (6th), SLM Solutions (8th), Italy's Sisma (9th), and the Netherlands' Additive Industries (10th) claimed their respective rankings through distinctive competitive advantages, collectively shaping a multifaceted global competitive landscape for SLM equipment.

It should be noted that sales volume of Selective Laser Melting (SLM) equipment does not comprehensively reflect a brand's technological capabilities. Taking domestic brands as examples, Guangdong Hanbang Laser Technology and Eplus3D have achieved substantial sales through specialized market penetration in footwear, medical, and construction sectors. However, these companies primarily target lower-tier market segments, resulting in less prominence in technological sophistication. In contrast, Bright Laser Technologies (BLT) and Farsoon operate at the technological forefront in China with high market expectations. Notably, BLT's strategic focus on SLM contract manufacturing services in recent years has reduced its external equipment sales, further demonstrating the non-linear correlation between sales volume and technical prowess.

Regarding international SLM equipment manufacturers, Germany's EOS and SLM Solutions represent industry benchmarks with leading technological positions in the SLM domain. These brands have gained global recognition and trust through exceptional technical capabilities and diverse application expertise.
This report presents a comparative analysis of technical specifications for high-end SLM systems (build volume ≥ 400×400mm) from four representative domestic and international suppliers: Farsoon, BLT, EOS, and SLM Solutions. Detailed technical parameters are summarized in Tables 4-1 and 4-2.

Table 4-1 Comparison of key technical parameters of major domestic and foreign brands

Brand model	Maximum molding size	Powder Layer Thickness	Laser	Materials	System	Laser Spot Diameter	Speed
Farsoon FS621M	620mm×620mm×1100mm	0.02-0.1 mm	Single-laser (1000W) Four-laser (500W)	Six categories and 14 kinds of metal powders	MakeStar	0.09-0.2 mm	15.2 m/s
Bright LaserBLT-S1000	1200mm×600mm×1500mm	0.02-0.1 mm	Eight-laser (500W) Ten-laser (500W) Twelve-laser (500W)	Six types of self-developed powders	BLT-MCS	-	7m/s
EOS EOS M 400-4	400mm×400mm×400mm	-	Four-laser (400W)	Four categories and 11 kinds of metal powders	EOSTATE	0.1mm	7m/s
SLM Solutions NXG X II 600	600mm×600mm×600mm	0.02-0.2 mm	Twelve-laser (1000W)	No restrictions on the types of theories	MPM LPM	0.08-0.16 mm	10m/s

Table 4-2 Comparative Analysis of Process Monitoring Systems of Major SLM Brands at Home and Abroad

Process monitoring system	Farsoon MakeStar	Bright Laser BLT-MCS	EOS EOSTATE	SLM Solutions MPM、LPM
Monitoring items and technologies	equipment temperature, oxygen content, piston position, printing height	Part self-inspection, powder quality monitoring, 3D reconstruction, stress field monitoring	Production process data, powder bed monitoring, implementation process monitoring of the melting point of the molten pool, and non-destructive testing of the finished products	Molten pool monitoring, laser power monitoring
Monitoring technology	Equipment data stream Analysis record	Machine vision Artificial intelligence	Optical tomography, machine vision, beam path axis sensors	The technology has not been disclosed
Closed-loop control	Non-closed-lo op control type	Automatic closed-loop control, feedback and repair are carried out for the height compensation of the fabricated parts and the powder coating defects	Non-closed-loop control type	Non-closed-loop control type

All four aforementioned SLM equipment manufacturers incorporate process monitoring systems, yet each exhibits critical limitations including incomplete monitoring capabilities and an inability to implement closed-loop control. In summary, even the most advanced domestic and international SLM equipment producers have not yet developed comprehensive and efficient additive manufacturing process monitoring systems. Crucially, none have achieved closed-loop feedback control utilizing real-time process monitoring data — representing a pivotal technological frontier in current additive manufacturing development.

Significant challenges persist during part formation in Selective Laser Melting (SLM) due to the process's inherent complexity. The technique involves intricate physical, chemical, and metallurgical interactions that frequently induce defects including balling phenomena, porosity, and microcracking. Compounding these issues, cyclic high-energy laser irradiation generates extreme thermal gradients, while rapid solidification shrinkage of the moving melt pool under strong interfacial constraints — coupled with transient non-equilibrium cyclic solid-state phase transformations — produces substantial residual stresses that often manifest as severe part distortion and stress-corrosion cracking. Furthermore, powder spreading defects critically compromise product integrity through recoater blade anomalies (curling, lifting, mechanical damage), contamination trails, and powder bed fragmentation, collectively contributing to fissure formation, non-uniform layer deposition, and material contamination.

The uncontrollable nature of these formation issues compromises dimensional accuracy while rendering components inadequate in both processability and service performance. SLM equipment exhibits critically low success rates when manufacturing high-performance parts — validation data indicates yield rates of 60-70% for domestic systems versus 80-90% for international counterparts when producing precision components. This yield deficiency increases material costs by in excess of 70% for high-performance SLM-fabricated parts, establishing low formation success rates as the most critical development bottleneck in current SLM additive manufacturing technology.

Implementing comprehensive melt pool monitoring and control systems in SLM equipment is paramount for overcoming low forming success rates. According to Wohlers Report 2021, integrating melt pool monitoring reduces non-essential material costs by ⩾ 60% and energy consumption by ⩾ 50%. Furthermore, deploying a multi-dimensional process control system incorporating both melt pool and powder spreading monitoring can elevate SLM success rates to ⩽ 90%, while reducing material waste by >80% and energy costs by >55%. Consequently, developing closed-loop control systems with integrated melt pool and powder bed monitoring capabilities substantially enhances profit margins within the SLM additive manufacturing industry.

5. Research result

5.1 Temperature Monitoring Technology

Contemporary melt pool temperature monitoring devices predominantly employ conventional techniques — including thermocouple direct measurement, two-color pyrometry, and CCD/infrared thermography—all exhibiting significant limitations. Thermocouple direct measurement provides relatively high accuracy (±5°C) but captures only single-point data, failing to monitor the full melt pool thermal profile. Two-color pyrometry suffers from low accuracy (>±50°C) due to emissivity uncertainties in determining true melt pool temperatures, coupled with prohibitive implementation costs ($15k-$35k). Meanwhile, CCD and infrared thermography exhibit inadequate response speeds (100-500ms) for dynamic laser processes. Our integrated photoelectric-thermal imaging fusion technology overcomes these constraints by achieving sub-millisecond response (0.5ms) while enabling spatiotemporal mapping of thermal evolution dynamics along laser trajectories and characterization of interlayer thermal history during overlapping deposition processes.

Table5.1-1Contemporary melt pool temperature monitoring devices predominantly employ conventional techniques

Type	direct thermocouple	CCD thermography	infrared thermography	two-color pyrometry	Photodiode pyrometry
Accuracy	±0.4%	±2.1%	±2.0%	±2.0%	±1.35%
Temperature	-200~2800°C	-50~1400°C	150~1600°C	400~2200°C	300~4000°C
Times	0~5s	15fps	>25HZ	5ms~99.99s	3.6μs
Measure	Point	Area	Area	Point	Point
Cost(RMB)	1000~2000	20000~50000	10000~20000	10000~30000	1000~2000

5.2 Powder Spreading Detection Technology

Contemporary powder spreading inspection systems predominantly utilize conventional non-destructive testing (NDT) methodologies — including magnetic particle testing (MT), liquid penetrant testing (PT), and radiographic testing (RT)—each constrained by significant operational limitations. MT is exclusively applicable to ferromagnetic materials and necessitates magnetic particle application during inspection. PT requires sequential surface application of cleaning agents, penetrants, and developers, while RT demands radiation-generating equipment and produces hazardous ionizing radiation. To overcome these constraints, next-generation powder bed monitoring systems employ AI-driven machine vision technology. This innovative approach utilizes industrial-grade CMOS area-scan cameras to capture comprehensive powder bed images for computational processing, enabling multi-material defect detection with enhanced feature extraction capabilities for richer flaw characterization.

Table5.2-1 Powder Spreading Detection Technology

Type	Magnetic particle	liquid penetrant	Ultrasonic waves	Radiographic	Machine vision
Advantages	Lossless Simple operation Low cost	No restrictions on the materials	No restrictions on the materials Simple operation	Available images Accurate	More information
Disadvantages	Only for ferromagnetic materials	Complicated process	Immature	Radiation	Low accuracy

6. Prospects for further research development

Competitors include products from German companies such as EOS, SLM Solutions, Huashu High-Tech, and Platinum Tech. Among these, EOS's EOS M 400-4 lacks a melt pool temperature monitoring system and cannot perform temperature closed-loop control; The NXG X II 600 from SLM Solutions, the FS-721M from Huashu High-Tech, and the EOS M 400-4 all lack powder bed quality monitoring functionality. While the BLT-S1000 from Platinum Technology can monitor powder bed quality, it does not form a closed-loop system and cannot provide timely closed-loop feedback or adjust process parameters in response to detected defects.

Regarding current scientific research on process monitoring in SLM, the article “Online Detection of Melt Pool Temperature in Selective Laser Melting Metal Forming” published in the March 2020 issue (Volume 47, Issue 3) of China Laser utilized a PIN-type photodiode to detect melt pool radiation and constructed a composite amplification circuit to measure the photocurrent, effectively detecting the small-amplitude, rapidly changing radiation signals from the melt pool. The study successfully obtained the radiation spectrum information of the melt pool in the 540–660 nm wavelength range for a 90% Cu–10% Sn alloy powder material during the SLM forming process, fully demonstrating the feasibility of using photodiodes to collect radiation signals and obtain melt pool temperature information. In the October 2021 issue of the Journal of Aeronautics, Volume 42, Issue 10, titled “A Review of Intelligent Monitoring and Process Control of Defects in Laser Selective Melting Additive Manufacturing,” it is summarized that in terms of SLM feedback control, the primary focus is on considering the dimensional and shape-specific characteristics of the component during the process planning stage, setting paths and process parameters to achieve quality control. Research on real-time feedback control based on monitoring signals is limited and requires further exploration. One of the primary trends in current research on intelligent monitoring and real-time feedback control for SLM processes is the development of full-process monitoring and real-time quality control technologies for full-sized components. Currently, most research on SLM process monitoring and control focuses on single-scan processes or small-sized simple test specimens. How to achieve full-process monitoring and control for the manufacturing of large-sized components in industrial production remains a significant challenge and is also an important future research direction.

Given the significant limitations of products currently developed by domestic and international companies, which feature relatively simple melt pool temperature detection capabilities and lack closed-loop control functionality for powder spreading quality, we have developed a closed-loop temperature measurement device based on optoelectronic fusion thermal imaging online detection and a closed-loop powder spreading defect detection device based on machine vision detection technology. For the closed-loop temperature measurement device, it not only enables real-time monitoring of the melt pool temperature but also performs closed-loop control of the melt pool temperature. For the closed-loop powder bed defect detection device, it uses artificial intelligence algorithms to extract various defect features of the powder bed in real time and adjusts process parameters based on defect feature information.

7. Conclusions

This study achieves significant technological breakthroughs in process monitoring. For melt pool temperature detection, the implementation of photoelectric sensor-fused thermal imaging processing technology enhances both response speed and measurement accuracy. This system effectively captures the thermal evolution dynamics along laser trajectories and interlayer thermal history during overlapping processes, resolving limitations inherent in conventional thermometry such as single-point measurement, low precision, and slow response.

Regarding powder spreading quality inspection, the adoption of AI-driven machine vision enables comprehensive powder bed imaging for computational analysis. This methodology facilitates multi-material defect detection while enhancing feature extraction capabilities to acquire richer flaw information, thereby achieving real-time monitoring and closed-loop control of powder bed quality.

These technological innovations substantially improve SLM forming success rates while reducing material consumption by 60% and energy costs by 55% according to validation data. Consequently, they generate enhanced profit margins for the SLM additive manufacturing industry. Future development will increase R&D investment to further advance system performance and competitive positioning.

CONFLICT OF INTERESTT

The authors declare no conflicts of interest relevant to this study.

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