



3D Printing for Smart Manufacturing Automatic Temperature Control Technology

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Abstract. The rapid development of intelligent manufacturing has propelled the widespread application of 3D printing technology across various fields. Meanwhile, the automatic temperature control technology, as a crucial factor in ensuring the quality of 3D printing, has garnered extensive attention. This paper aims to review the research status, technical system, future development trends, and challenges of 3D printing automatic temperature control technology oriented towards intelligent manufacturing. By analyzing the current temperature monitoring technologies, control algorithms, and closed-loop control systems, it explores the application prospects of emerging technologies such as digital twins, artificial intelligence, and multi-sensor fusion in this field. Moreover, it proposes future research directions and suggestions to provide references for researchers and practitioners in relevant fields. This research holds significant importance for optimizing 3D printing processes, improving product quality, and promoting the intelligent advancement of manufacturing industries. Furthermore, advancing temperature control technology is essential for achieving high-precision, high-efficiency, and sustainable production in next-generation smart manufacturing systems.

Keywords: 3D Printing, Smart Manufacturing, Automatic Temperature Control, Closed-loop Control System, Intelligent Algorithm

1 Introduction

Intelligent manufacturing, as an emerging production model, emphasizes the intelligentization, automation and high efficiency of the production process through the deep integration of information technology and manufacturing technology[1]. 3D printing technology, as an important part of intelligent manufacturing, has been widely used in aerospace, automotive manufacturing, medical and other fields by virtue of its ability to quickly transform digital models into solid parts. However, precise control of temperature during 3D printing plays a crucial role in ensuring print quality, improving productivity, and enabling the fabrication of complex structures.

In the 3D printing process, temperature control directly affects the physical processes such as melting, flow, and solidification of the printed material, which in turn determines the accuracy, strength, and surface quality of the part [2]. Traditional tem-

perature control methods are often difficult to meet the requirements of complex printing tasks, while automated temperature control technology is able to monitor and adjust the temperature changes during the printing process in real time, thus significantly improving the quality and stability of 3D printing. Therefore, in-depth study of 3D printing temperature automatic control technology for intelligent manufacturing is of great theoretical and practical significance for promoting the further development and application of 3D printing technology.

This paper will focus on the temperature control technology in the context of the integration of 3D printing and automation technology, combing the current technology path, analyzing the development status of key control technologies and intelligent algorithms, and exploring the prospects for the industrial application of automated temperature control technology and the future development direction.

2 3D printing temperature control technology overview

2.1 Introduction to the 3D printing process

3D printing technology, also known as additive manufacturing, is a manufacturing process that builds three-dimensional solid parts by stacking materials layer by layer. The core of this lies in the decomposition of a complex 3D model into a series of 2D layers and the stacking of materials layer by layer, culminating in the desired solid structure. Currently, 3D printing technology covers a variety of different processes, mainly including Fused Deposition Modeling (FDM), Selective Laser Melting (SLM), and StereoLithography Apparatus (SLA), etc. These processes differ significantly in principle, material selection, and application scenarios, but all involve the layer-by-layer stacking of materials to form a three-dimensional solid part.

Fusion deposition molding(FDM). The FDM process is one of the most widely used 3D printing technologies today. The basic principle is that filamentary materials (e.g. PLA, ABS, etc.) are melted through a heated nozzle and then deposited layer by layer on the printing platform following a preset path. As the nozzle moves and the material builds up layer by layer, the desired 3D solid part is eventually formed. The advantages of the FDM process include low equipment costs, simple operation, and a wide variety of materials, making it suitable for rapid prototyping and low-volume production. However, the FDM process requires a high degree of temperature control, and the precise control of the nozzle temperature and print platform temperature directly affects the quality of material melting, flow and interlayer bonding. If the nozzle temperature is too high, it may lead to excessive melting of the material and uncontrolled flow, thus affecting the dimensional accuracy and surface quality of the parts; while too low a nozzle temperature will prevent the material from melting sufficiently, resulting in poor interlayer bonding, or even clogging of the nozzle. Therefore, precise temperature control is one of the key factors in the FDM process to ensure print quality.

Selective laser melting(SLM). The SLM process is a 3D printing technology used primarily for metallic materials. The basic principle is to use a high-energy laser beam to selectively melt metal powder according to a preset path, so that the powder is melted and solidified layer by layer, and ultimately form the desired three-dimensional metal parts. SLM process has the advantages of high precision, high strength, and strong ability to manufacture complex structures, and is widely used in aerospace, automotive manufacturing and other high-end manufacturing fields. Temperature control is also critical in the SLM process. The temperature of the laser bath directly affects the melting, flow and solidification processes of the metal powder, which in turn determines the microstructure and mechanical properties of the part. If the melting pool temperature is too high, it may lead to excessive melting, evaporation or even splashing of the metal powder, thus affecting the surface quality and dimensional accuracy of the parts; while too low a melting pool temperature will prevent the metal powder from melting sufficiently, resulting in unfused defects inside the parts. Therefore, the SLM process requires precise control of the temperature of the laser bath to ensure uniform melting and solidification of the metal powder.

Stereo lithography apparatus(SLA). The SLA process is a photosensitive resin-based 3D printing technology. The basic principle is to use ultraviolet light to irradiate the liquid photosensitive resin layer by layer by a preset path, so that it undergoes a photopolymerization reaction and is cured. The advantages of the SLA process are high printing accuracy and good surface quality, which are suitable for manufacturing parts with complex shapes and fine structures. However, the SLA process is relatively insensitive to temperature, mainly because the curing process of photosensitive resins depends mainly on UV light irradiation rather than temperature changes. Nonetheless, ambient temperature and print platform temperature will still have some effect on the flow and curing speed of the photosensitive resin. For example, a high ambient temperature may cause the viscosity of the photosensitive resin to decrease, thus affecting its fluidity and the quality of interlayer bonding; while a low ambient temperature may slow down the curing of the photosensitive resin, or even cause incomplete curing. Therefore, in the SLA process, although temperature control is of relatively low importance, it is still necessary to maintain appropriate ambient and print platform temperatures to ensure a smooth printing process.

Different 3D printing processes have different requirements for temperature control, mainly due to their differences in material properties, molding principles and process parameters. Therefore, in practical applications, it is necessary to select appropriate temperature control strategies and technical means according to specific process requirements and material properties to achieve high-quality 3D printing.

2.2 Importance of temperature control

Temperature is one of the key factors affecting the quality of 3D printing. In the 3D printing process, temperature control directly affects the physical processes such as

melting, flow, curing, and interlayer bonding of the printed material, which in turn determines the precision, strength, and surface quality of the part. Accurate temperature control can ensure that the material has good fluidity and bonding in the printing process, thus improving the dimensional accuracy and surface quality of the parts; at the same time, reasonable temperature control can also effectively reduce the generation of thermal stress and improve the mechanical properties and internal quality of the parts. The following is an analysis of the specific importance of temperature control in different 3D printing processes:

Effects on material melting and flow. In FDM and SLM processes, the melting and flow of material is a key process to achieve layer-by-layer stacking. If the temperature is too high, the material may overmelt, resulting in uncontrolled flow, which can affect the dimensional accuracy and surface quality of the part. For example, in the FDM process, too high a nozzle temperature may lead to excessive melting of the material inside the nozzle, making it too fluid, resulting in uneven stretching and stacking of filamentary material during deposition, which ultimately leads to rough surfaces of the parts and increased dimensional deviations. In the SLM process, the high temperature of the laser melting pool may lead to excessive melting, evaporation or even splashing of the metal powder, thus affecting the surface quality and dimensional accuracy of the parts. On the contrary, if the temperature is too low, the material will not be able to melt sufficiently, resulting in poor flow or even clogging of the nozzle or unfused powder. For example, in the FDM process, too low a nozzle temperature may lead to filamentary materials can not be completely melted, so that it appears in the deposition process of the interlayer bonding is not firm, the surface of the hole and so on; in the SLM process, the laser melting pool temperature is too low may lead to the metal powder can not be sufficiently melted, so that unfused defects in the interior of the parts, seriously affecting the mechanical properties of the parts.

Effect on interlayer bonding. The quality of interlayer bonding is one of the most important factors in determining the strength and integrity of a 3D printed part. In the FDM process, precise control of the nozzle temperature and print stage temperature is critical to the quality of the interlayer bond. Too high a nozzle temperature may result in excessive melting of the material, preventing it from bonding adequately with the next layer during deposition, while too low a nozzle temperature may prevent the material from melting adequately, resulting in poor bonding between layers. In addition, the control of the temperature of the printing platform affects the quality of the bond between the first layer of material and the platform. If the platform temperature is too high, it may lead to excessive diffusion of the material on the platform, thus affecting the dimensional accuracy and surface quality of the part; while too low a platform temperature will prevent the material from bonding sufficiently with the platform, leading to warping or shedding of the part during the printing process. In the SLM process, the control of the laser molten pool temperature is equally important for the quality of interlayer bonding [3]. If the melting pool temperature is too high, it may lead to exces-

sive melting of the metal powder, which may result in shrinkage stress during solidification, affecting the quality of interlayer bonding; while too low a melting pool temperature will prevent the metal powder from melting sufficiently, resulting in poor interlayer bonding or even unfused defects.

Effect on thermal stress. Thermal stresses are stresses that occur due to temperature changes during the 3D printing process. During the printing process, the material is cooled from a high-temperature molten state to room temperature, generating thermal stresses. If the temperature is not properly controlled, thermal stresses may cause warping, cracking and other defects in the part, thus affecting the quality and performance of the part. For example, in the FDM process, rapid changes in nozzle temperature and print platform temperature may result in large thermal stresses within the part, leading to warpage during part cooling. The rapid cooling of the laser melt pool in the SLM process also generates large thermal stresses, which may lead to cracks inside the part or even affect the mechanical properties of the part if the temperature is not properly controlled. Therefore, reasonable temperature control can effectively reduce the generation of thermal stress and improve the quality and performance of parts.

Impact on printing speed and efficiency. Temperature control also affects the speed and efficiency of 3D printing. In the FDM process, proper control of the nozzle temperature ensures material flow and deposition speed, thus increasing printing speed and efficiency. If the nozzle temperature is too high or too low, it can result in poor material flow, which can reduce print speed. In addition, the control of the temperature of the printing platform affects the deposition rate and quality of the first layer of material. In the SLM process, the reasonable control of the laser melt pool temperature can ensure the rapid melting and solidification of the metal powder, thus improving the printing speed and efficiency. If the melt pool temperature is too high or too low, it will affect the melting and solidification rate of the metal powder, thus reducing the printing speed. Therefore, precise temperature control can not only improve the quality and performance of 3D printing, but also increase the printing speed and efficiency, thus realizing efficient and high-quality 3D printing.

Temperature control has a crucial role in the 3D printing process. It not only affects the quality of melting, flow and interlayer bonding of the printed material, but also the thermal stress, printing speed and efficiency of the part. Therefore, achieving precise temperature control is the key to improving 3D printing quality, efficiency and performance.

3 Temperature automatic control technology system

3.1 Temperature monitoring technology

Temperature monitoring is the basis for realizing automatic temperature control. Accurate, real-time temperature data is a prerequisite to ensure that the control system can

effectively regulate the temperature. At present, the temperature monitoring technology commonly used in 3D printing mainly includes contact and non-contact methods.

Contact temperature monitoring. Contact temperature monitoring measures temperature by placing the sensor in direct contact with the object being measured. Common contact temperature sensors include thermocouples and thermistors.

Thermocouples are temperature sensors based on the Seebeck effect, where an electric potential is generated in a loop when two different metal conductors form a closed loop and are at different temperatures. Thermocouples have the advantages of wide measurement range, high accuracy and fast response time, and are widely used in the FDM process to measure the temperature of nozzles and printing platforms. For example, in FDM printers, thermocouples are typically mounted near the nozzle, enabling real-time monitoring of the nozzle's temperature changes and feedback of the data to the control system. However, thermocouples have some limitations, such as the need to be in contact with the object to be measured, the possibility of environmental interference, and the possibility that long-term use may lead to a decrease in measurement accuracy.

A thermistor is a semiconductor device whose resistance changes with temperature. Its advantages are small size, low cost, high sensitivity, suitable for more sensitive to temperature change occasions. In 3D printing, thermistors are commonly used to monitor the temperature of the printing platform. For example, in some FDM printers, a thermistor is mounted on the printing platform and is capable of monitoring temperature changes in the platform in real time and feeding the data back to the control system. However, thermistors have a relatively narrow measurement range and their nonlinear characteristics require calibration and compensation to improve measurement accuracy.

Non-contact temperature monitoring. Non-contact temperature monitoring determines the temperature of an object by measuring the infrared radiation it emits. Common non-contact temperature sensors include infrared thermometers.

Infrared thermometers are based on Planck's law and calculate the temperature of an object by measuring the intensity of infrared radiation emitted from its surface. Infrared thermometers have the advantages of non-contact measurement, fast response time, wide measurement range, etc. They are especially suitable for high-temperature environments and rapid measurement. In the SLM process, infrared thermometers are widely used for real-time temperature monitoring of the melt pool to quickly capture transient temperature changes in the melt pool, thus effectively minimizing defects. For example, in SLM printers, an infrared thermometer is mounted near the laser head to monitor temperature changes in the melt pool in real time and feed the data back to the control system. However, the measurement accuracy of infrared thermometers may be affected by the characteristics of the object surface (e.g., emissivity, reflectivity) and they are relatively expensive.

Data acquisition and processing. The temperature data collected by the temperature sensor needs to be processed by the data acquisition system so that the control system

can obtain accurate temperature information in real time. Data acquisition systems typically include components such as signal amplifiers, filters, and analog-to-digital converters (ADCs). Signal amplifiers are used to amplify the weak signals output from the sensors, filters are used to remove the noise signals, and ADCs convert the analog signals to digital signals for processing by the control system. In the 3D printing process, the performance of the data acquisition system directly affects the accuracy and real-time temperature monitoring. For example, in FDM printers, the data acquisition system needs to be able to respond quickly to changes in nozzle and print stage temperatures and transmit the data to the control system in real time. In order to improve the accuracy and reliability of data collection, it is often necessary to calibrate and compensate the collected data. For example, by modeling the calibration of temperature sensors, measurement data can be corrected to improve measurement accuracy.

3.2 Temperature control algorithm

The temperature control algorithm is the core of realizing automatic temperature control. Stable control of temperature can be achieved by adjusting the power of the heating or cooling equipment according to the temperature feedback data. Currently, commonly used temperature control algorithms include the traditional PID control algorithm and its improved algorithms.

Conventional PID control algorithm. The PID control algorithm is a classical feedback control algorithm that controls the heating or cooling equipment based on temperature deviations by adjusting three parameters: proportional (P), integral (I) and differential (D). The basic principle of PID controller is: when the temperature deviation is large, the heating or cooling power is quickly adjusted by the proportional term; when the temperature deviation is small, the steady state error is eliminated by the integral term; the temperature trend is predicted by the differential term, and the heating or cooling power is adjusted in advance, so as to improve the stability of the control and the response speed. PID control algorithm has the advantages of simple structure, easy to implement, adaptability and so on, which is widely used in 3D printing temperature control. For example, in FDM printers, the PID controller adjusts the power of the heater in real time based on the deviation between the nozzle temperature and the target temperature to stabilize the nozzle temperature near the target value. However, due to the complexity and nonlinear characteristics of the 3D printing process, traditional PID control algorithms are difficult to achieve the desired control effect in some cases. For example, during the printing process, factors such as the thermal properties of the material, changes in ambient temperature, and the mechanical structure of the printer may affect the accuracy and stability of temperature control.

Improved PID control algorithm. In order to improve the performance of PID control algorithms, researchers have proposed a series of improved algorithms, including fuzzy PID control algorithms, adaptive PID control algorithms, and temperature control algorithms based on deep learning.

The fuzzy PID control algorithm combines the advantages of fuzzy logic and PID control. Fuzzy logic is able to deal with uncertainties and ambiguities in the system, and the PID parameters are adjusted online by fuzzy rules, thus improving the robustness and adaptability of the system. For example, in the FDM printing process, the fuzzy PID controller can dynamically adjust the PID parameters according to the temperature deviation and the rate of change of the deviation, so that the system can maintain good control performance under different working conditions. It is shown that the fuzzy PID control algorithm can significantly improve the stability of the nozzle temperature and reduce the temperature overshoot and fluctuation. For example, one study used a fuzzy PID algorithm that resulted in a significant improvement in the stability of the FDM print nozzle temperature and a reduction in temperature overshoot by more than 11.5%.

The adaptive PID control algorithm automatically adjusts the PID parameters by estimating the system model parameters in real time to adapt to temperature changes under different operating conditions. The Adaptive PID controller automatically learns the thermal properties of the material and ambient temperature changes during the printing process, allowing for more precise temperature control. For example, in the SLM printing process, the adaptive PID controller can automatically adjust the laser power and scanning speed according to the change of the melt pool temperature, thus realizing the stable control of the melt pool temperature. It is shown that the adaptive PID control algorithm can effectively improve the control accuracy of the molten pool temperature and reduce the generation of defects.

With the development of artificial intelligence technology, temperature control algorithms based on deep learning are gradually applied to 3D printing temperature control. The deep learning algorithm learns and predicts temperature data by building a neural network model, which is able to automatically extract complex temperature features and patterns for more accurate temperature control. For example, in the FDM printing process, the temperature control algorithm based on deep learning can predict the trend of the nozzle temperature and adjust the power of the heater in advance by learning the historical temperature data [4], so as to realize a more stable temperature control. It has been shown that the temperature control algorithm based on deep learning can significantly improve the accuracy and response speed of temperature control [5], which is suitable for 3D printing temperature control under complex working conditions.

3.3 Closed-loop control systems

A closed-loop control system is a system that can automatically adjust the control strategy based on feedback information, and is widely used in 3D printing temperature control. The closed-loop control system achieves stable temperature control by monitoring temperature changes in real time and adjusting the power of the heating or cooling equipment according to the temperature deviation [6].

System components. A typical closed-loop temperature control system consists of a temperature sensor, controller and actuator.

The temperature sensor monitors temperature changes during printing in real time and feeds the measured value back to the controller. As mentioned earlier, commonly used temperature sensors include thermocouples, thermistors, and infrared thermometers. Choosing the right temperature sensor is critical to improving the performance of a closed-loop control system.

The controller calculates the control signal according to the deviation between the set target temperature and the actual measured value and sends it to the actuator in accordance with a certain control algorithm. Commonly used control algorithms include traditional PID control algorithms and their improved algorithms such as fuzzy PID, adaptive PID and deep learning based temperature control algorithms.

The actuator regulates the heating or cooling equipment according to the signals from the controller to achieve stable temperature control. In 3D printing, common actuators include heaters and cooling fans. For example, in FDM printers, heaters are used to heat the nozzles and print stage, and cooling fans are used to regulate the temperature of the nozzles and print stage.

Advantages of closed-loop control systems. The closed-loop control system has good stability and anti-interference ability, which can effectively reduce temperature fluctuations and improve printing quality [7]. For example, in the FDM process, the use of a closed-loop temperature control system can reduce nozzle temperature fluctuations from $\pm 10^{\circ}\text{C}$ to within $\pm 1^{\circ}\text{C}$, significantly improving the quality of the interlayer fusion and molding accuracy. In addition, the closed-loop control system is capable of automatically adapting to different printing materials and process parameters to improve the versatility and flexibility of the system [8]. For example, in the SLM process, a closed-loop control system automatically adjusts the molten pool temperature according to different metal powder materials and laser parameters, resulting in high-quality metal part printing.

Challenges of closed-loop control systems. Despite the many advantages of closed-loop control systems, they still face a number of challenges in practical applications. First, the accuracy and response speed of the sensor directly affects the performance of the closed-loop control system. If the measurement accuracy of the sensor is low or the response speed is slow, it may result in the control system not being able to obtain the temperature information timely and accurately, thus affecting the control effect. Second, the complexity and computational efficiency of the control algorithm is also an important issue. For example, although deep learning-based temperature control algorithms can achieve more accurate temperature control, they have higher computational complexity and require longer training time and higher computational resources. In addition, the design and commissioning of a closed-loop control system requires consideration of the stability and robustness of the system. For example, in FDM printers, the closed-loop control system is able to adapt to different printing materials and ambient temperature variations to ensure stable operation of the system [9].

4 Future development trends

4.1 Direction of technology evolution

With the continuous development of intelligent manufacturing technology, 3D printing temperature automatic control technology is also moving towards the direction of higher intelligence and more accurate control [10]. Among them, the application of digital twin technology has great potential. Digital twinning is a technology that works by creating virtual models corresponding to physical entities and using real-time data for simultaneous updating and simulation analysis. In 3D printing temperature control, digital twin technology can create virtual models synchronized with the physical printing system to monitor and simulate temperature field changes in real time [11]. Active adjustment of control parameters, thus effectively avoiding defects caused by temperature fluctuations during the printing process. In addition, artificial intelligence and machine learning algorithms will further penetrate into the development of temperature control systems. Using machine learning methods can establish an accurate mapping relationship between process parameters and print quality, predict the optimal temperature control strategy in real time [12], and realize the adaptive adjustment of temperature parameters. The use of such intelligent algorithms will effectively enhance the ability of the 3D printing process to adapt to material differences, environmental changes and complex geometries to achieve higher manufacturing precision and stability. At the same time, the application of multi-sensor fusion technology in automatic temperature control system will be strengthened. The future temperature control system will integrate many types of sensors, such as thermocouples, infrared thermometers, vision cameras, etc., to fuse various types of data in real time for collaborative control [13], in order to more comprehensively capture the temperature changes during the printing process, and to achieve a more refined and accurate closed-loop control.

4.2 Sustainable manufacturing

In the context of global advocacy of green manufacturing, the research and development of 3D printing temperature automatic control technology also needs to pay more attention to sustainable development. Future temperature control systems will further focus on energy optimization and material recycling [14]. For example, intelligent control algorithms can reduce energy waste and minimize energy consumption through precise temperature control [15]. At the same time, the combined use of temperature control systems and recycled materials can also significantly reduce the carbon footprint of the manufacturing process, boosting additive manufacturing toward an environmentally friendly green manufacturing model. Statistically, the use of recycled plastics as 3D printing materials can reduce associated carbon emissions by more than 50 percent. In addition, by recycling used plastic products into printing materials, the carbon footprint and energy consumption of the manufacturing process can be significantly reduced. In terms of energy optimization, the future automated 3D printing system will pay more attention to energy management and efficiency improvement, and is

expected to achieve raw material recycling, zero waste process, intelligent optimization of energy consumption, and truly build a new paradigm of green manufacturing.

5 Conclusion

This paper introduces the automatic control technology of 3D printing temperature for intelligent manufacturing, and analyzes the current development status and advantages of the current technology from the temperature monitoring technology, control algorithm to the closed-loop control system. The study shows that the application of automatic temperature control technology effectively improves the quality consistency and manufacturing precision of 3D printing, reflecting an important shift from traditional manual regulation to automated intelligent regulation. However, the current technology still faces some challenges, such as the improvement of sensor accuracy and response speed, the optimization of control algorithms under complex process conditions, and the system integration of multi-technology fusion.

Interdisciplinary cooperation: Strengthen the interdisciplinary research of materials science, control theory, computer science and other multidisciplinary research to promote the innovation and development of temperature control technology. **Emerging technology integration:** in-depth exploration of digital twin, artificial intelligence, multi-sensor fusion and other emerging technologies in the application of 3D printing temperature control, to achieve more intelligent and accurate control. **Sustainable Manufacturing:** Focus on the combination of temperature control technology and green manufacturing, optimize energy use efficiency, promote the application of recyclable materials, and reduce the environmental impact of the manufacturing process. **Standardization and industrialization:** establish unified temperature control technology standards and specifications, accelerate the industrialization and application of advanced temperature control technology, and promote 3D printing technology towards large-scale production and industrial application.

3D printing temperature automatic control technology for intelligent manufacturing is of great significance in improving manufacturing quality and efficiency. With the continuous development and innovation of the technology, its application prospect will be broader.

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