Configuration and Adjustment of Substrate Preheating Device

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Abstract. Laser Metal Deposition Shaping (LMDS) is a state-of-the-art technology that combines rapid prototyping and laser processing. There are many factors affecting the quality, precision, microstructure and performance of LMDS-deposited parts. Among them, substrate preheating is a significant one since it can change the heat history of the LMDS process. Preheating is often used to reduce the residual stresses and the risk of thermal distortion and cracking. In this work a set of substrate preheating device for LMDS system employed with dual-channel control, namely intelligent PID temperature control and realtime serial-port temperature acquisition and feedback control, is designed and developed. In addition, the heating up rule gained through the relative experiment is introduced to reduce the overshoot amplitude of substrate preheating device by cascade control method. The results show that not only can this substrate preheating device realize the dual-channel control and continuous adjustment of substrate preheating temperature, but also can realtime collect and record the substrate temperature.

Introduction

Laser Metal Deposition Shaping (LMDS) is being developed since a few years for rapid manufacturing [1,2] and rapid tooling [3,4] applications. In this process parts are built by overlapping consecutive layers of a laser melted material on the prepared substrate. Since cooling involves heat conduction to the bulk, the material in each layer will undergo successive thermal cycles as new layers are added. These short duration thermal cycles can induce solid-state transformations in the previously deposited layers, and lead to progressive modification of their microstructure and properties. In the process of LMDS, the thermal history will differ from point to point in the part and it will depend on the processing parameters, scanning pattern, build-up strategy, substrate preheating temperature and geometry of the part being built. As a result, the type and extent of the solid-state phase transformations induced by the thermal field in the part may vary from point to point, thus leading to the complex distribution of microstructure and properties observed experimentally [5].

The LMDS process holds the features of collective energy input and rapid heating and cooling, which induces the considerable temperature gradient and even thermal stress between as-formed part and substrate. As the thermal stress reaches the material limit, the crack and rupture will be generated with the parts. Accordingly, the improvement of temperature distribution in forming process, the reduction of substantial temperature gradient and thermal stress, and the constraint of crack and distortion caused by deposition shaping become the important and urgent issues to LMDS process. Among the influencing factors of thermal history, substrate preheating is an effective one to resolve the above-mentioned issues. Since the preheated substrate promotes better adhesion and therefore better heat transport for the initial deposited powder, it can reduce the temperature gradient between part and substrate, and make the temperature field uniform and stable. As a result, a set of substrate preheating device for LMDS system is developed with flying colors and presented in detail.
Substrate Preheating Device

**Hardware Configuration.** The hardware of substrate preheating device of LMDS system mainly consists of substrate preheater, intelligent PID temperature controller, and realtime acquisition and feedback controller of substrate preheating temperature. The substrate preheating device is employed with dual-channel control, namely, the intelligent PID temperature control and the realtime temperature acquisition and feedback control by serial communication. They form the close-loop control individually. They can work independently, as well as do collaboratively. The specific hardware configuration of substrate preheating device is shown in Fig. 1.

1. Substrate preheater  2. Thermocouple  3. Intelligent PID controller  4. Motion control card  5. Computer  6. Interface converting module between RS232 and RS485  7. Temperature collecting module

![Fig. 1 Sketch of the substrate preheating device for LMDS](image)

**Substrate Preheater.** The working conditions of substrate preheater are high-temperature and dusty. Besides, the substrate preheater must meet the requirements that it should realize rapid warming, and then keep constant temperature. Accordingly, the substrate preheater is designed to be composed of such parts: stainless steel heating pipe, box, refractory porcelain plate, insulating asbestos and copper plate, etc, as illustrated in Fig. 2. The heating pipe is a high-power stainless steel electric heating pipe, so it has the characteristics of rapid warming and dust resistance, and is not easy to generate short-circuit. The box is the two-layered structure, and the heat insulating material is filled in the middle. This construction can insulate heat and preserve temperature, as well as decrease the start frequency and increase the durability of heating pipe. The refractory porcelain plate is used to fix the heating pipe on the box, separate the heating pipe from the baseplate of preheater, and avoid the temperature of preheater bottom is too high due to the contact with heating pipe. The copper plate is supported by the box and put on the heating pipe. The copper can satisfy the requirement of rapid warming because of the superb thermal conductivity. Meanwhile, the copper plate with certain thickness possesses the high thermal capacity, which can uniformize the substrate heating, reduce the varying frequency of preheating temperature, and decrease the start frequency of heating pipe.

**Intelligent PID Temperature Controller.** The substrate preheating temperature can be individually controlled by intelligent PID temperature controller. The preheating temperature can be continuously regulated from room temperature to 600°C. The intelligent PID temperature circuit is mostly composed of DC power, intelligent PID temperature controller, armored PT100 platinum thermal resistor, and solid state relay. The DC power is employed to supply power to the intelligent
PID temperature controller, whose input end is connected with the PT100 platinum thermal resistor installed on the side of copper plate of substrate preheater, thus realizing the substrate preheating temperature collection. In addition, the output end of intelligent PID temperature controller is linked with the high-power stainless steel heating pipe through the solid state relay. When the preheating temperature is lower than the setting one, the intelligent PID temperature controller makes connection with the solid state relay, and then the latter is connected up to heating pipe, thus heating the copper plate; when the preheating temperature reaches the setting one, the intelligent PID temperature controller is disconnected with the solid state relay, and then the latter makes disconnection with heating pipe, thereby stopping heating the copper plate. In this way, the closed loop control for substrate preheating temperature is formed.

1. Refractory porcelain plate  2. Supporting block of copper plate  3. Thermocouple  4. Inwall connecting piece  5. Outwall connecting piece  6. Stainless steel heating pipe  7. Outwall of preheater  8. Inwall of preheater  9. Insulating asbestos  10. Baseplate of preheater

![Fig. 2 Sketch of the internal structure of the substrate preheater](image)

**Realtime Temperature Acquisition and Feedback Controller.** The realtime temperature acquisition and feedback controller of substrate preheating temperature through computer serial port can realtime monitor and record the preheating temperature, and substitute the intelligent PID temperature controller for the control of substrate preheating temperature. The temperature acquisition part of this controller mainly includes interface conversion module and temperature acquisition module of serial communication. The signal transfer protocol adopts the ASCII command/response protocol. Besides, the temperature control part mostly comprises the Advantech PCI-1750 I/O control card and solid state relay. When the computer realtime controls the acquisition and feedback of serial temperature, as the host computer, it takes advantage of the serial communication technology to realize the interface standard conversion from RS232 to RS 485 through the interface standard conversion module. The front-end equipment adopts the ADAM-4018 thermocouple temperature acquisition module with RS485 interface standard to connect with PT100 platinum thermal resistor, which can convert the analog signal of preheating temperature to the digital signal, thus achieving the serial-port realtime acquisition process of substrate temperature. Meanwhile, the computer would compare the realtime acquired substrate temperature with the previously assigned preheating temperature. If the former is lower than the latter, the computer will make connection with solid state relay by the Advantech PCI-1750 I/O control card, and cause the heating pipe to continuously heat the substrate; if the former is greater than the latter, the computer will disconnect the solid state relay by I/O control card, thus preventing the heating pipe from heating.
the substrate. In this way, the control of substrate preheating temperature is fulfilled. In the process of realtime acquisition and feedback control by computer serial port, the serial communication between computer and interface standard conversion module is realized through the VC++ language programming.

**Adjustment Procedure.** The temperature of substrate preheating device of LMDS system adopts the dual-channel control, namely the intelligent PID temperature control and the realtime temperature acquisition and feedback control by computer serial port. The two kinds of temperature control methods can be applied individually or simultaneously. When they are employed all together, the intelligent PID controller is used to control the substrate preheating temperature, while the realtime temperature acquisition and feedback controller is used to realtime display and record the variation of substrate preheating temperature with time. However, the thermal inertia of substrate preheating device is very great, so the precise control of preheating temperature is considerably difficult. Fig. 3 shows the substrate temperature variation curve gained by computer serial-port acquisition at the preheating temperature of 100°C, 200°C, 300°C, 400°C, and 500°C. As illustrated in Fig. 3, when the substrate preheating temperature is relatively low, the overshoot of system is considerably great. However, the overshoot amplitude increases by degrees with the gradual decrease of setting value of substrate preheating temperature. For example, if the substrate preheating temperature is set to 100°C, the ultimate substrate temperature can be up to 125.8°C at the most, so the overshoot amplitude reaches 25.8%; but if the substrate preheating temperature is set to 500°C, the highest substrate temperature will reach 504.4°C, so the overshoot amplitude is only 0.88%. Meanwhile, the variation period of substrate temperature shortens by degrees as the setting value of substrate preheating temperature gradually rises. Typically, if the substrate preheating temperature is set to 100°C, the variation period of substrate temperature is about 1400s; but if the substrate preheating temperature is set to 500°C, the variation period of substrate temperature is proximately 200s.

![Substrate preheating temperature curves collected by computer serial port](image)

**Table 1** Heating up law of substrate preheating temperature (Unit: °C)

| Preheating temperature | Setting temperature | Room temperature | Maximum temperature |
|------------------------|---------------------|------------------|---------------------|
| 50                     | 32                  | 24.9             | 60.8                |
| 100                    | 70                  | 24.2             | 103.3               |
| 200                    | 172                 | 24               | 198.8               |
| 300                    | 283                 | 24               | 300.6               |
| 400                    | 385                 | 24               | 396.3               |
| 500                    | 495                 | 24.6             | 506.8               |
In order to reduce the overshoot, the heating up experiment is performed, and the heating up law is obtained as listed in Table 1. Through the cascade control, the heating up law is introduced to substrate preheating system. As can be seen in Fig. 4, if the substrate needs to be preheated to 200°C, the substrate heating temperature can be set to 174°C according to heating up law. Then, when the practical substrate temperature is up to 200°C, the substrate preheating temperature can be reset to 200°C. In this way, the system overshoot could get inhibition to a great degree, and the overshoot amplitude goes down from 8.9% to 2.85%, which basically meets the test accuracy demand.

![Fig. 4 Overshoot control curves of substrate preheating temperature](image)

**Summary**

Summarily, a set of substrate preheating device special for LMDS system is designed and manufactured in accordance with the processing characteristics and heat transfer theory of LMDS technology. It adopts intelligent PID temperature controller and realtime serial-port temperature acquisition and feedback controller. Not only can it realize the dual-channel control and continuous adjustment of substrate preheating temperature, but also can realtime collect and record the substrate temperature. Besides, the overshoot amplitude of substrate preheating device can be reduced through the introduction of heating up law by the cascade control method.

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**References**

[1] X. Wu and J. Mei: Near Net Shape Manufacturing of Components Using Direct Laser Fabrication Technology. J. Mater. Process. Tech., Vol. 135 (2003), p. 266-270.

[2] L. Wang, L.Y. Qin, M. Tong and K. Xiang: Multistep-Like Behavior and Error Evaluation Method in Rapid Prototyping Manufacturing. J. Shenyang Univ. Technol., Vol. 30(3) (2008), p. 318-321.

[3] D. Morgan: New Metal-Fabrication Application. Industrial Laser Solutions, Vol. 15(1) (2000), p. 8-10.

[4] J. X. Lou, D. Y. Li, Z. L. Zhang, H. B. Zhang and X. Q. Dong: Rapid Steel Mould Manufacture Based on Arc Spraying. J. Shenyang Univ. Technol., Vol. 28(3) (2006), p. 255-257.

[5] L. Costa, R. Vilar and T. Réti: Simulating the Effects of Substrate Pre-heating on the Final Structure of Steel Parts Built by Laser Powder Deposition. Solid Freeform Fabrication Symposium, (2004), p. 643-654.