Research status of on-line monitoring of laser metal deposition

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Abstract. The process of laser metal deposition was easy to be affected by fluctuations of environment and process parameters, leading to the deviation of melt pool temperature or deposition morphology and so on. Accumulation of small deviation would result in the instability of deposition process and lead to the failure of forming. Therefore, the on-line monitoring of laser metal deposition process was studied, involving thermal history of forming parts, temperature and size of melt pool, deposition morphology and forming defects, and so on. In this paper, the on-line monitoring technologies, such as thermocouple temperature measurement, infrared thermal imaging, high-speed camera and other monitoring methods, were introduced, and the open-loop monitoring, closed-loop feedback control and closed-loop feedforward control technologies were illustrated in detail. According to the research situation, the future development of on-line monitoring in laser metal deposition was prospected.

Keywords: laser metal deposition, on-line monitoring, infared temperature measurement, thermal imaging, high-speed photography

With the development of science and technology, new requirements such as high efficiency, high performance and green energy saving have been put forward for modern manufacturing[1]. Traditional manufacturing technology has gradually been unable to meet the current new needs. Laser metal deposition technology (LMD), which is also called laser cladding, laser rapid prototyping, provides a new way for modern industrial production. It has great application value in the manufacture of high-complex parts[2], the manufacture and repair of large load-bearing structural parts[3] and the coating modification of material surface[4]. It can not only shorten the construction period, reduce costs, save strategic precious metal materials, but also protect the environment. And the performance of the parts can exceed the level of the traditional parts.

LMD forming process is a micro-pool establishment and non-stationary solidification process. The temperature, shape and size of the molten pool are easily affected by various factors. The accumulation of fluctuations may cause instability of deposition process and ultimately lead to failure of forming. However, these interference factors are extremely complex in the actual environment, and it is difficult to completely eliminate them. Based on this, researchers have developed a variety of monitoring technologies in order to maintain the stability of the forming process through closed-loop control of the temperature, shape and size of the molten pool.

There are five main monitoring techniques in LMD: (1) temperature measurement by thermocouple, (2) temperature measurement of molten pool by infrared thermometer, (3) temperature field measurement of molten pool by thermal imager, (4) molten pool melting transition behavior monitoring by high-speed camera, (5) Other monitoring methods such as laser scanning. This paper will introduce the research status of monitoring technology in LMD from these aspects.

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1. Monitoring Technology

1.1. Thermocouple Temperature Measurement Technology

Thermocouple is the most traditional temperature probe, which is accurate and cheap. The temperature measurement method is single point contact temperature measurement, which requires direct contact with the material, causing it unable to be used for temperature measurement of molten pool. In the LMD process, thermocouples are usually used to measure the thermal history of printed parts, and the data are used for finite element simulation or analysis of the structure transformation of printed parts.

Ya et al.[5] simulated the laser cladding process by finite element method, and monitored the thermal history at different positions of the substrate using thermocouples, as shown in figure 1 (a). Finally, the error between simulation results and experimental measurements is less than 5%, which verifies the accuracy of the simulation calculation, as shown in figure 1 (b).

Heigel[6] and Ma[7] also used thermocouples to measure the thermal history at different positions of the substrate during wire-feed and powder-feed cladding, and compared it with the simulation results to analyze the energy absorption during laser cladding. Khan[8] and Meng[9] analyzed the microstructural evolution of materials during deposition using the thermal history measured by thermocouples.

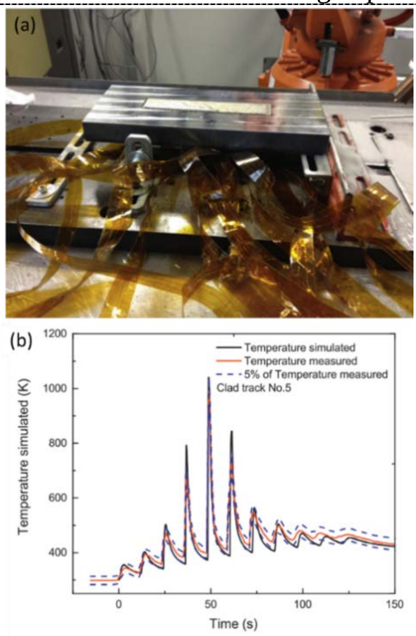

Figure 1. (a) Thermocouple temperature measuring device; (b) thermal history from thermocouple measurement and simulation[5]

1.2. Infrared Temperature Measurement Technology

Infrared thermometer detects temperature by infrared signal emitted by heating object, which is non-contact. Infrared thermometer is mainly divided into two kinds: one is monochromatic thermometer, which receives only one bands of infrared light and determines the temperature of the object by the intensity of the light; the other is colorimetric thermometer, which receives two bands of infrared lights and determines the temperature by the ratio of the strength of the two bands. Because infrared light is vulnerable to environmental factors such as smoke and dust, monochromatic thermometer is vulnerable to interference. Colorimetric thermometer has strong anti-interference because it takes the ratio of the strength of two bands.

Infrared thermometer, different from thermocouple, is a non-contact single-point temperature sensor, so it is often used to detect the temperature of molten pool in the LMD process. Song et al.[10] integrated the infrared thermometer into the printing system to keep it moving synchronously with the cladding head and the molten pool, so as to monitor the temperature change of the molten pool and realize the closed-loop control of laser power accordingly.

Infrared thermometer can also replace thermocouple to monitor the thermal history of printed parts. As shown in figure 2, Muvvala et al.[11,12] used infrared thermometer to collect the fixed-point thermal history and analyzed the microstructure evolution during cladding. Infrared thermometer can collect not only the temperature below the melting point, but also the temperature within a certain range above the melting point, which is more advantageous than thermocouple temperature measurement.

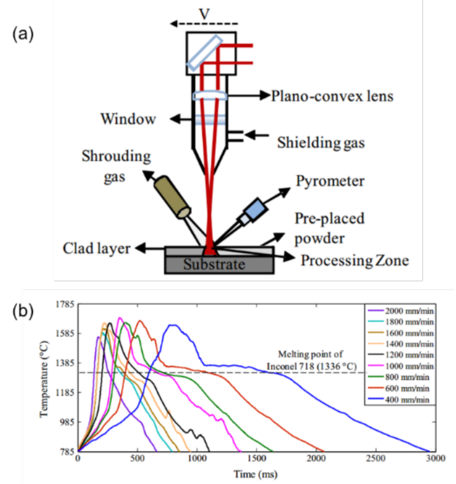

Figure 2. (a) Schematic diagram of temperature measurement principle of infrared thermometer; (b) thermal history at different scanning speeds[11]

1.3. Thermal Imaging Technology of Temperature Field

The signal intensity of infrared or visible light found at different temperature points of the object under test is different. When imaging in charge coupled device (CCD) or complementary metal-oxide-semiconductor (CMOS), each point presents different gray or brightness equivalents. According to the signal intensity of each point in the image, the temperature field of the object under test can be analyzed.

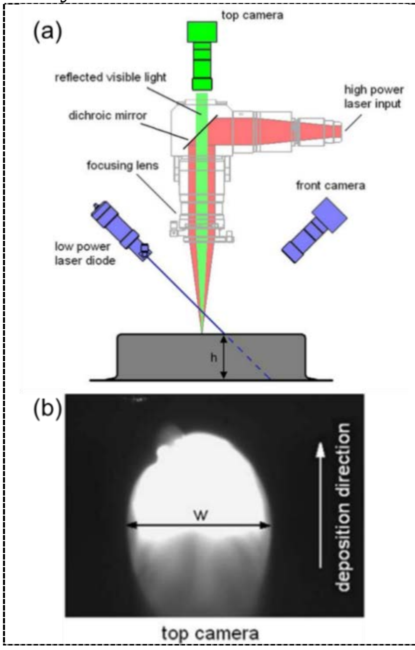

Figure 3. (a) Schematic diagram of CCD thermal imaging device; (b) schematic diagram of molten pool image and width monitoring[13]

Using infrared thermal imaging, not only the temperature, but also many other information, such as the shape and size of the molten pool, can be obtained by image analysis. As shown in figure 3, Heralić et al.[13] designed a CCD thermal imaging system to monitor the temperature field of the molten pool in wire laser additive manufacturing. The width of molten pool was calculated by using the image of molten pool temperature field, and the closed-loop control of laser power was carried out, which maintained the stability of the forming process. Yong et al.[14] monitored the temperature field of molten pool in wire-feed cladding by CCD, and extracted the area, width and length of molten pool by calculation. Lei[15] and García de la Yedra[16] carried out similar studies. In addition, Govekar[17] and Kuznetsov[18] used infrared thermal imaging to observe the droplet formation process at the tip of wire during wire-feed rapid prototyping, which provided a reference for the adjustment of process parameters.

In addition to analyzing the shape and size of molten pool, some researchers used infrared thermal imaging technology to monitor forming defects. Ding et al.[19] studied the thermal behavior of wire laser additive manufacturing by using infrared thermal imager, and predicted the deposit width and poor fusion defects during deposition. Khanzadeh et al.[20] proposed a dual statistical process monitoring method based on infrared thermal imager, which combines image feature extraction and dimension reduction to identify local defects or anomalies in deposition process.

1.4. High-speed Photography Technology

High-speed camera has very high frame rate. With special filter lens and supplementary lighting equipment, it can take instantaneous phenomena such as melting, transition, solidification and splash of materials in the process of LMD, and then playback them slowly, which can provide the most intuitive visual image data for research.

Liu et al.[21] built a high-speed monitoring system in hot wire laser deposition, and observed the melting transition process of wire and the influence of different hot wire voltage on arc striking, as shown in figure 4. Torkamany et al.[22] used high-speed camera to observe the melting transition process from wire to keyhole, studied the influence of different process parameters on the shape of wire tip and metal melting transfer, and revealed the interaction mechanism between transverse oscillation laser and metal. Zhang[23] used high-speed camera to capture the image of molten pool, and compared the shape of molten pool with that calculated by finite element method.

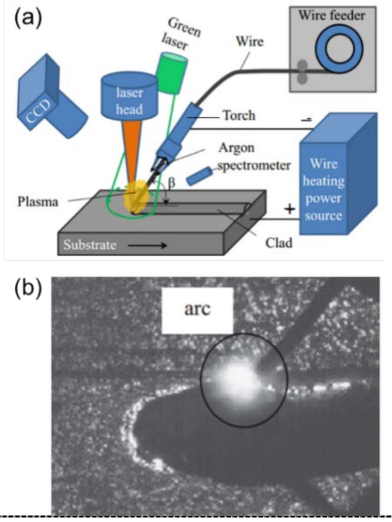

Figure 4. (a) Schematic diagram of high-speed photography; (b) real-time image of molten pool under hot wire condition[21]

1.5. Other Monitoring Techniques

In addition to the above types of monitoring methods, there are some special monitoring methods in LMD. Heralić et al.[24] designed a system for measuring the surface topography of the previous deposited layer by using diode laser. Based on this system, the wire-feed speed was controlled by iterative control algorithm, and then the deposition height of the next layer was controlled to ensure the stability of the deposition process. As shown in figure 5, Hagqvist et al.[25] used the resistivity of liquid bridge to monitor the current surface topography in real-time in wire-feed LMD. Through closed-loop control system, the surface morphology was smoother. Heigel et al.[26] used laser distance measuring instrument to monitor the substrate deformation in real time during cladding process.

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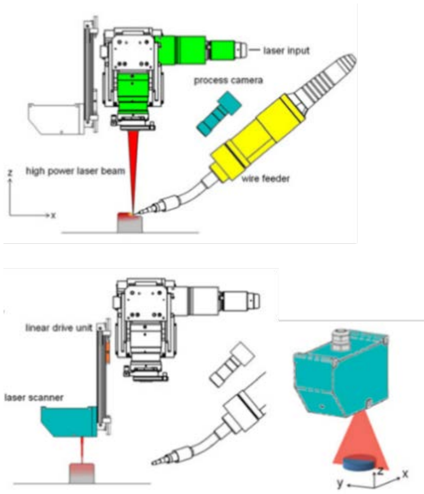

Figure 5. Schematic diagram of laser scanning detection for surface morphology[24]

1.6. Compound Monitoring Technology
Many of these monitoring methods are not used alone. Heigel et al.[6] simultaneously used thermocouples and laser ranging sensors to monitor the thermal history and deformation of the substrate. Song et al.[10] used both CCD and infrared thermometer to control the deposition height and the temperature of molten pool in a closed-loop way. Heralićet al.[13] also used thermal imaging technology of temperature field and laser diode profile temperature measurement technology to control the width and height of molten pool. The composite application of different monitoring technologies increases the complexity of the monitoring system, but also provides more abundant information, which is the trend of future development.

2. Application Mode
On-line monitoring is an important assistant method of LMD. Its main purpose is to improve the forming stability and quality. However, the application mode of monitoring technology is diverse. At present, there are three main applications of on-line monitoring: (1) open-loop monitoring, (2) closed-loop feedback control, (3) closed-loop feedforward control. Feedback control and feedforward control belong to closed-loop control technology, but they are different in detail. Therefore, they are divided into two sub-categories for detailed introduction.

2.1. Open-loop Monitoring Technology
Open-loop monitoring is not a process control method, but just a data collection method. Only after manual analysis, the measured data can be adjusted to improve the forming stability and quality. For example, Liu et al.[21] directly observed the phenomenon of arc starting at the tip of metal wire under different hot-wire voltages by using high-speed camera, so that the limit value of hot-wire voltage was directly obtained, so as to achieve the purpose of adjusting process parameters. Some technologies, due to their own limitations, are only used to study the mechanism of microstructure evolution. For example, Ya[5], Heigel[6] and Ma[7] used thermocouple to measure thermal history, mainly to compare with the finite element simulation calculation result or to analyze the microstructure evolution, but it could not provide an effective reference for process parameter adjustment. This is because the thermocouple can only monitor the thermal history of a certain point in the non-molten pool and cannot reflect the actual state of the molten pool.

Open-loop monitoring can provide a lot of data for process optimization, but it is inefficient because it requires manual analysis. Moreover, the open-loop monitoring data cannot reflect the real-time state of the forming process. Only an overall adjustment of the process parameters can be made by open-loop monitoring, and the process parameters in a certain stage or instantaneous process parameters cannot be finely adjusted, which cannot effectively improve the anti-interference ability of the forming process.

2.2. Closed-loop Feedback Control Technology

The closed-loop feedback control is a kind of monitoring technology which adjusts the process parameters online in real time after the monitoring data is analyzed and fed back to the numerical control system. As shown in figure 5, Song et al.[10] analyzed the temperature and height of the molten pool measured by pyrometer and CCD respectively, and adjusted the laser power in real time by using the feedback system, thus improving the stability of forming process. Through CCD thermal imaging, Heralić et al.[13] analyzed the width of molten pool and controlled the laser power in real time online.

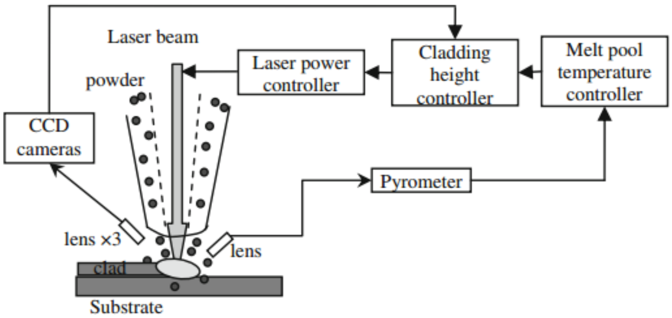

Figure 6. Closed-loop feedback control system based on infrared temperature measurement and thermal imaging[10]

The closed-loop feedback control is a promising monitoring method, which can significantly improve the forming stability and quality. Moreover, the addition of the feedback control system does not affect the forming efficiency. The closed-loop feedback control is suitable for controlling process parameters with fast response speed. As shown in figure 7, when the laser power is increased instantly, its influence is quickly reflected on the temperature and size of the molten pool, with no or little lag effect[13].

2.3. Closed-loop Feedforward Control Technology

The closed-loop feedforward control is a monitoring technique that monitors and analyzes and adjusts process parameters before the end of each layer or section of deposition. This monitoring technique is usually used to control process parameters with hysteresis effect. As shown in figure 7, the wire-feed speed will be reflected in the deposition height in the time of about 3 s after it is increased, with a certain lag effect[13].

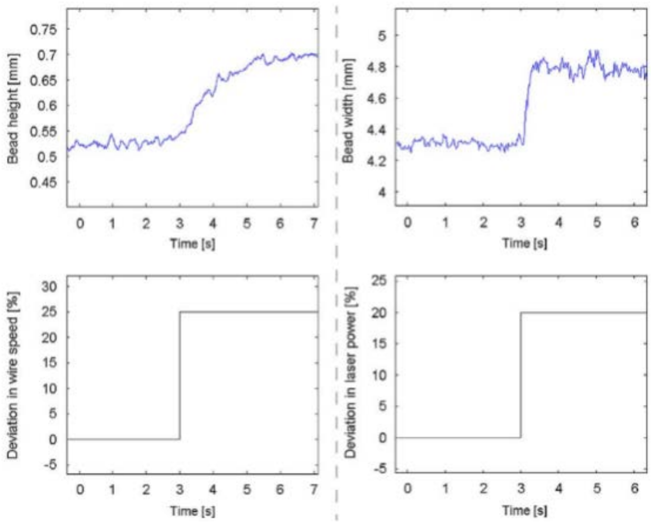

Figure 7. Response time of fuse height and width when wire-feed speed and laser power change suddenly[13]

Therefore, feedforward technique is adopted by Heralić for monitoring. The height of the previous layer is measured before each section is deposited, and the wire-feed speed is adjusted in advance. As shown in figure 5, Heralić [24] also use a similar feedforward technique in the monitoring of surface morphology. Before each layer is deposited, the surface morphology of the previous layer is measured first, and then process parameters of each segment of the path of the next layer are adjusted. The closed-loop feedforward control has a good effect on the control of process parameters with hysteresis, which is complementary to the feedback control. However, because part of feedforward control needs to stop the deposition process first before the process parameters is adjusted, it results in the reduction of forming efficiency.

3. Conclusions And Prospects

In recent years, on-line monitoring technology has made great progress, which provides powerful data support for LMD research and plays a very important role in its research. In these monitoring methods, thermocouple temperature measurement, infrared temperature measurement and temperature field imaging are temperature-related detection. Thermocouple temperature measurement has the greatest limitation. It can only measure the temperature of fixed point, and can not get more information. Infrared thermometer can completely replace the work of thermocouple to monitor the thermal history. At the same time, it can also track the temperature of molten pool in real time. Temperature field imaging can get more information, so it is also the most widely used. High-speed cameras are mainly used to observe the melting transition process of materials. The information obtained is relatively small, the shooting time is relatively short, and the equipment is extremely expensive. Therefore, their applications are relatively small. Among other monitoring methods, laser scanning is a more effective feedforward control technology and a more promising monitoring technology. These monitoring technologies have their own focus. Current research is no longer limited to the use of a single monitoring technology and simple data monitoring, but more and more inclined to the integration of multi-technology and closed-loop control.

At present, the research of LMD online monitoring is still weak in closed-loop control. First of all, most of the current rapid prototyping technology is still not mature enough, and still stays at the research stage, such as wire laser additive manufacturing, which has not yet reached the stage of industrial application, and the demand for closed-loop control is still small. Secondly, there is no dedicated independent control module to ensure its efficient data acquisition, analysis and feedback. Therefore, this paper holds that the on-line monitoring technology will make great progress in the following aspects: (1) the development and application of high-speed analysis module or software for on-line monitoring data to solve the shortcomings of the current monitoring technology, such as slow data analysis and lagging response; (2) the development and application of new monitoring algorithms such as in-depth learning to realize intelligent control of forming process; (3) the development and application of high-precision and high-sensitivity monitoring sensors can provide more accurate data and faster response for LMD process.

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