Proc. of the 9th Intl. Conf. of Asian Society for Precision Engg. and Nanotechnology (ASPEN 2022)
15–18 November 2022, Singapore. Edited by Nai Mui Ling Sharon and A. Senthil Kumar
doi://10.3850/978-981-18-6021-8_OR-01-0034

Metrology applications in in-situ process monitoring of additive manufacturing

Baoxi Xu[1#], Yuanjie Liu[1], Li Wang[1], Shengkai Yu[1], Chengwu An[1], Jing Zhang[1], Shaochun Ye[1], Yan Fan[1], Jie Fang[1], Alvin Kuang Shuan Tan[2], Chee Kit Choy[2] and Youxiang Chew[2]

1 National Metrology Centre, Agency for Science, Technology and Research (A*STAR), 8 CleanTech Loop, #01-20, Singapore 637145 Singapore
2 Singapore Institute of Manufacturing Technology, Agency for Science, Technology and Research (A*STAR), 2 Fusionopolis Way, Singapore 138634 Singapore
Corresponding Author / Email: xu_baoxi@nmc.a-star.edu.sg, TEL: +65-67149268

KEYWORDS: Metrology, Additive manufacturing, In-situ melt pool monitoring, Direct energy deposition

In this presentation, the status of metrology applications and standard developments in AM will be reviewed briefly first. The focus will be on metrology in the in-situ melt pool monitoring. The measurement principles of the different melt pool monitoring methods will be introduced. The applicable calibration methods, and advantages and disadvantages for them to be used for the AM process close loop control will be analyzed.

A system for the in-situ melt pool temperature distribution measurement and process close loop control has been developed with measuring the melt pool parameters in real time for the direct energy deposition (DED) AM at hundreds of frames per second. The real system calibrations in temperature and dimension will be illustrated and the results will be discussed. Finally, the experiments of adaptive feedback close loop controls for the different melt pool parameters with a DED AM machine will be demonstrated, and the results indicates that the close loop control can keep the controlled parameter in constant vert well. Compared to the printing without close loop control, the printing performance with the close loop control system has been improved significantly.

1. Introduction

Additive manufacturing (AM) plays a key role in Industrial 4.0. However, its extensive implementation is currently being inhibited by two factors: (1) lack of universal guidelines for metrology, inspection and standardization and (2) quality consistence of the manufactured parts. To produce parts with predictable and consistent quality, new measurement techniques with the metrological methodology must be developed to complement existing measurement methods. Metrology will be a critical tool for the characterization and optimization of AM capabilities. It will be a very important in first identifying and then applying mitigation strategies to obtain the required quality.

The quality of the manufactured part is mainly determined by the behaviors of the melt pool in the process. An accurate in-situ monitoring of the melt pool is very important for predicting the process quality and realizing a precise close loop control based on the monitoring results. To obtain reliable and accurate monitoring results, metrological methodologies must be used in the monitoring system calibration.

In this presentation, after brief review of metrology applications and standard developments in AM, the methods for in-situ melt pool temperature measurements will be discussed. Finally, a developed system for in-situ melt pool temperature measurement and process close loop control as well as its experimental results will be introduced.

2. Status of metrology applications and standard developments in AM

Metrology is the measurement science. It covers the unit definitions of measurement parameters, development measurement protocols, production of artifacts that act as measurement standards to allow traceability of measurements, and analysis of measurement uncertainties and accuracies [1]. The wide applications of every technology and product are inseparable from metrology. Metrology is used in raw material/ device qualification, production process monitoring and control, as well as product qualification and certification. All the standards for qualification and certification of products are based on metrology to define measurement standard, measured parameter value with its uncertainty and accuracy.

There are two main international organizations in AM related

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standard developments: International Organization for Standardization (ISO) and ASTM International. They developed their own AM standards at the beginning. After they banded together and developed the Additive Manufacturing Development Structure (AMDS), both work together for AM standard development. More than 30 standards have been approved and more than 45 standards are in development [2, 3]. Figure 1 illustrates the standards framework developed by them for development of AM standards.

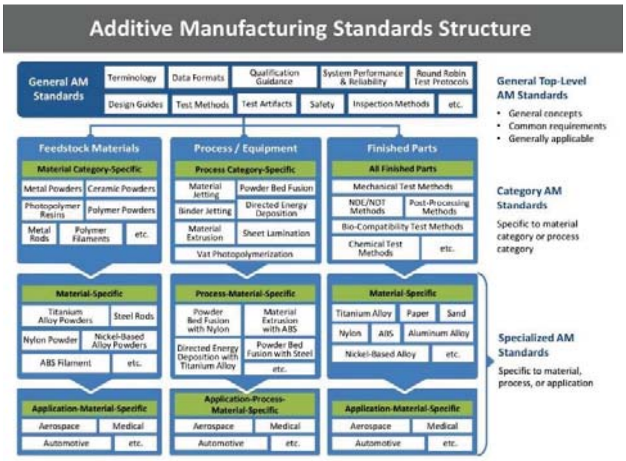


Fig. 1 Standards framework developed by ASTM and ISO for development of additive manufacturing standards [4].

America Makes & American National Standards Institute (ANSI) Additive Manufacturing Standardization Collaborative (AMSC) was established in 2016 to coordinate and accelerate the development of industry-wide AM standards and specifications consistent with stakeholder needs and thereby facilitate the growth of AM industry. It published "Standardization Roadmap for Additive Manufacturing" [5], which identified 93 open gaps in AM standard developments in 5 areas: design, process and materials, qualification and certification, nondestructive evaluation and maintenance. The most recent standard developments are to fill those gaps.

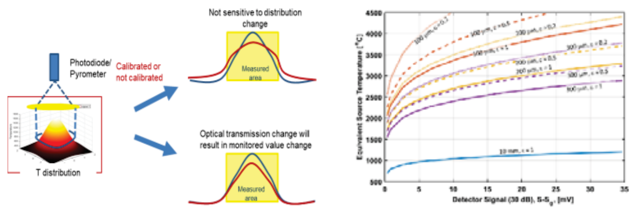
3. In-situ melt pool temperature monitoring techniques

The quality of the manufactured part is mainly determined by the behaviors of the melt pool in the process. The temperature and size of the melt pool are the most important parameters to be monitored to provide assurances that a part was made to a required specification. The monitored data is not only for understanding the performance of the melt pool, but also for realizing close loop control for a consistent quality of the processed parts.

There are two categories of optical arrangements for the remote melt pool temperature monitoring: off-axis monitoring and co-axis monitoring. In off-axis monitoring arrangement, the monitor captures the melt pool temperature information from a side of optical axis of the process laser beam [6,7]. In the most cases, the monitored area does not follow the melt pool movement during process. It is suitable for monitoring and investigating the temperature historic variation of the melt pool. However, it is not suitable for process in-situ close loop control. In co-axis monitoring method, monitor sensors capture the melt pool temperature information along the optical axis of the process laser beam. In this arrangement, the monitored area always follows the melt pool movement during the process. It is suitable for real time close loop control. In this paper, the study focuses on the co-axis monitoring method.

The temperature monitoring systems can be classified into two: one-dimensional (1D) monitoring system and two-dimensional (2D) monitoring system.

1D monitoring system uses a pyrometer or a photodiode as the sensor for the melt pool temperature measurement, as shown in Fig. 2 (a). The sensor collects the integrated thermal radiation of the melt pool over a defined area. The obtained data is one number for one capture (1D data). The advantage of this method is that the volume of the captured data and processed data are small, which is applicable to high speed in-situ monitoring and close loop control. However, it is sensitive to the change of the optical transmission loss between melt pool and the sensor, and it is not sensitive to the change of the temperature distribution in a certain range. Figure 2(b) plots the measurement results of the corresponded temperatures of the sensor detected signals at different thermal source sizes [8]. It indicates that a detected signal could represent the different temperatures, which depends on the thermal source size. If 1D monitoring system is used for a close loop control, due to the contamination, the change of optical transmission will cause the monitored value change and further control value change. When the temperature distribution varies within a certain range, the system cannot generate an error signal for the close loop control. Therefore, 1D monitoring is not suitable for accurate close loop control.

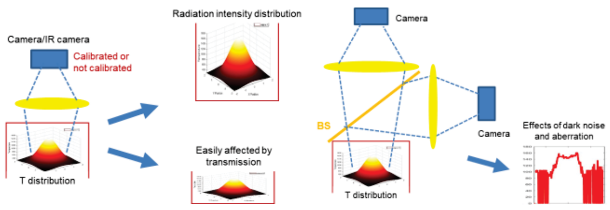


(a) (b)

Fig. 2 (a) 1D melt pool temperature monitoring system and its shortages used for close loop control; (b) Equivalent source temperature as a function of detector signal at different source diameters and uniform emissivity values.

2D monitoring system uses one thermal camera or industrial camera to captures melt pool image and analyses the melt pool parameters for close loop control [9-11], as shown in Fig.3(a). The advantage of this method is that it can obtain 2D information about melt pool, such as size and intensity distribution. However, due to the temperature dependence of the emissivity, they are not accurate temperature information. They are also easy to be affected by the optical transmission loss if they are used for close loop control. Another 2D method uses two cameras to capture two melt pool images at two different wavelengths [12], as shown in Fig. 3(b). Based on Plank's law, the temperature distribution of the melt pool is obtained. It gets less effect from the change of optical transmission loss and its temperature measurement results are more accurate. The shortcomings are that the optical system aberration and camera dark noise will affect the measured temperature values at related low temperature range.

To make the temperature measurement and close loop control more accurate, the temperature dependent emissivity of the measured object must be known. It is a very challenge work to measure the temperature dependent emissivity until temperature up to 2000K (the melting points of many alloys are around 1700K), especially for metal powder materials.



(a) (b)

Fig. 3 Different kinds of melt pool monitoring systems and their shortages used for close loop control: (a) 2D method with one (thermal) camera and (b) 2D method with two cameras.

4. Development of in-situ melt pool temperature distribution monitoring and close loop control system

A system for the in-situ melt pool temperature distribution measurement and manufacturing close loop control is developed, and its schematic configuration is shown in Fig. 4. It consists of an optical system and cameras for melt pool radiation image capture, a Field Programmable Gate Arrays (FPGA) board for the thermal image processing, melt pool parameter data extraction and error signal generation, and a digital to analogue convertor (DAC). It generates the close loop control signal to adjust laser source output power based on the deviation of the monitored parameter from its set value. The system can work for the direct energy deposition (DED) AM machine at hundreds of frames per second.

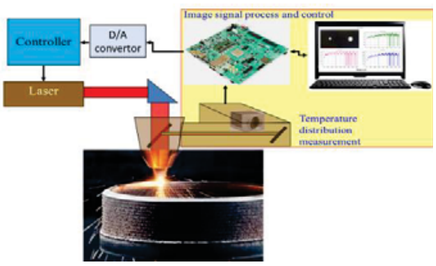


Fig. 4 Schematic configuration of the developed in-situ melt pool temperature distribution measurement and close loop control system.

Figure 5 illustrates the generated feedback control signal of the developed system at the open loop condition and 100fps. It clearly shows that when the measured parameter value is within the allowed tolerance of the set value, the generated laser control signal keeps the same. When the measured value is larger than the set value (out of tolerance), the control signal will decrease. Versa vice, when the measured value is smaller than the set value (out of tolerance), the control signal will increase. It indicated that the function of monitoring and feedback control signal generation can work very well.

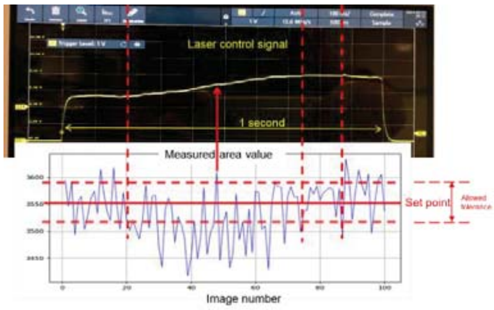


Fig. 5 Relationship between the generated feedback laser control signal and measured control parameter value in open loop condition.

5. Printing results with close loop control system

The experiments for melt pool temperature distribution measurements and adaptive feedback close loop controls for the different melt pool parameters have been carried out with a DED AM machine. Figure 6 is the photo of experiment system showing the prototype of the developed system installed in a DED machine.

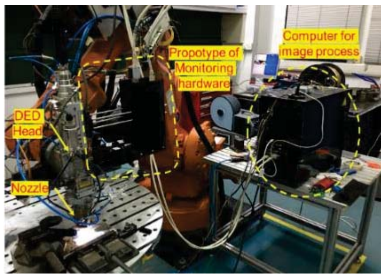


Fig. 6 Picture of the prototype of the developed monitoring and close loop control system installed in a DED AM machine.

The real printing results for the blocks are shown in Fig. 7. The print strategy is that after printed one layer along one direction, the printing direction is turned 90 degree to print next layer, as shown in Fig. 7(a) and (b). The melt pool area is set as the control parameter. The measured area variations of melt pool without and with area control (set value of 50000 (pixel numbers)) are illustrated in Fig. 7(c) and (d) respectively. Without control, the laser power keeps the same for printing different layers. As the layer number increases, the accumulation of the thermal energy makes the higher layer having higher temperature, which results in larger melt pool area. Therefore, the melt pool area increases gradually without control. However, the area keeps almost a constant when area control is applied. Figure 5(e)) shows the printed blocks with and without control at the same printing parameter setting. The part printed with control has sharper edges and smoother surfaces than the part printed without control. The control maintains the melt pool size as a constant through adjusting/reducing the laser power and makes the printing with almost same melt pool condition for different layers. The imprints on the bottom base plate (top view) also show that more heat energy has been transferred to the plate in printing without control. Therefore, the printing performance with control has been significantly improved.

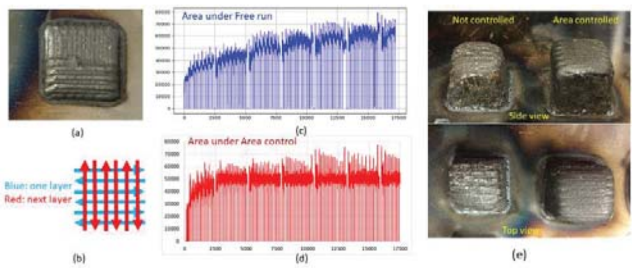


Fig. 7 Experimental results. (a) half printed block, (b) printing strategy, (c) measured area results without area control, (d) measured area with area control (set value: 50000 pixels), (e) Pictures of printed blocks with and without controls.

6. Conclusions

Metrology applications and standard developments are important for AM adoption by verity industries. More effects on them are still expected in the qualifications and certifications of raw material, process and the printed parts.

In the in-situ melt pool temperature monitoring, different kinds of monitoring methods have different advantages and disadvantages. For more accurate temperature monitoring and control, 2D methods are the first choice. 1D monitoring method shows its advantages in the high speed.

A high accurate monitoring and close loop control system with 2D method has been developed. The experiment results indicate that the close loop control performs very well for keeping the controlled melt pool parameter in constant. Compared to the printing without close loop control, the performance of printing with the close loop control system has been improved significantly.

ACKNOWLEDGEMENT

This work was supported by Singapore RIE2020 Advanced Manufacturig and Engineering (AME) IAF-PP project with grant No. A1893a0031.

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