Development of Sensing and Control System for Robotized Laser-based Direct Metal Addition System

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Abstract: Laser-based direct metal addition (LBDMA) is a promising directed energy deposition technology that is well suited for the production of complex metal structures, low-volume manufacturing, and high-value component repair or modification. LBDMA is finding wide application in the automotive, biomedical, and aerospace industries. However, the process reliability and the repeatability of finished components are still problems. This work offers a solution by developing a sensing and control system for the robotically controlled 8-axis LBDMA system developed at the Research Center for Advanced Manufacturing of Southern Methodist University, Dallas, TX. The developed system consists of sensing and control units for the powder flow rate and the molten pool size. An optoelectronic sensor was developed to sense the powder flow rate. It is a main component in an on-line control system of powder flow rate in a LBDMA system. An infrared imaging setup was installed on the laser head to monitor the top full-field view of the molten pool. A simple proportional integral derivative (PID) controller, combined with feed-forward compensation was used to build a closed-loop control system for achieving a uniform molten pool size. Two L-shaped single-bead walls were built with and without closed-loop control, respectively. A good performance on achieving uniform geometry by closed-loop control of the molten pool size was approved.

Keywords: Laser-based direct metal addition, Sensing and control, Powder flow rate, Molten pool size

1. Introduction

Laser-based direct metal addition (LBDMA) is a promising directed energy deposition technology that builds metal components layer upon layer by forming a molten pool on the substrate by a focused laser beam in which metal powder/wire is fed. This technology is well suited for the production of complex metal structures, low-volume manufacturing, and high-value component repair or modification [1, 2]. Industries are driving the development of LBDMA in the areas of automotive, biomedical, and aerospace. Thanks to

the high spatial resolution of the well-defined laser beam, the state-of-the-art LBDMA has been growing to challenge building near net shape components from their CAD files. Several challenges have been identified that inhibit the broader application of this technology including process sensing and control [3], microstructure optimization [4], build size, production rate of the process, and production of components with a functionally graded composition. The Research Center for Advanced Manufacturing (RCAM) at Southern Methodist University has been developing a robotically controlled 8-axis LBDMA system targeting solutions and improvements for those challenges [5, 6]. This paper describes the development of the process sensing and control system for the LBDMA system.

Currently, fluctuations in the process parameters (e.g., laser power, scanning speed, and powder flow rate), environment (e.g., inert gas pressure, powder distribution, ambient temperature, and humidity), and process itself (e.g., surface tension, flow in the molten pool, and reflection of the molten pool) often deflect the process from the pre-optimized condition, resulting in defects in the finished components. The process reliability and dimensional repeatability of the finished components are still problems that should be solved [7]. Real-time process sensing and control have the potential to address these concerns, but they are still in their infancy [3]. For a LBDMA system, sensing and control of the powder flow rate and molten pool size are highly significant in achieving greater quality in the finished component.

A controllable powder delivery system ensures a stable and consistent addition process. Powder delivery control provides the ability to adjust on-line the powder flow rate based on need [8]. It also enables the production of components with functionally graded composition. The key element for achieving powder delivery control is to measure the powder flow rate in real-time. Many novel measurement techniques have surfaced in recent years to measure the powder flow rate in pneumatic conveying pipelines. The electrostatic sensor with an intrusive rod electrode [9-11] was reported to be inexpensive and simple to implement. But it is quite sensitive to moisture content, particle size, and chemical composition [12]. Based on flow tomography technology, a capacitance sensor [13] and radiometric sensor [14] were developed to monitor the powder flow rate. However, they are not widely used because this type of sensor demonstrates non-uniformity in the sensing field, poor resolution, and low sensitivity. S. Tallon *et al.* [15] developed an acoustic sensor using active acoustic signals to measure the solids concentration in dilute-phase pneumatic conveying pipelines. The sensor needed an accurate value of slip between the velocity of gas and solids,

which was difficult to obtain. Song *et al.* [16] developed a digital imaging system that enabled measurement of the powder flow rate and particle velocity. But it was not compact enough for use with the LBDMA system. Based on the detection of light reflected by suspended particles, the optical sensor was first developed by Nieuwland *et al.* [17] using multi-fiber sensors. Hu D. *et al.* [18] simplified the design and used it to monitor the powder flow rate for LBDMA system. In their work, more than a half second was needed to get a stable powder flow rate due to the measuring white noise and the low signal acquisition rate of 10 Hz. A compact, powder flow-rate sensor with an acceptable measurement accuracy and measurement time lag for real-time control is needed.

Sensing and control of the molten pool size is a critical issue regarding the geometrical accuracy of the finished component [2, 19, 20], as well as the reliable bonding between layers and the thermal history that governs the microstructural properties of the finished component [4]. The key sensors used to achieve monitoring and control of the molten pool include infrared pyrometers [21-24] and thermocouples [25]. Infrared pyrometers including photodiodes [26-28] and digital cameras [18, 28] are the primary options for monitoring and control of the molten pool in the existing literature. These options provide a wide temperature measurement range and the capability of non-contact measurement [7]. T. Hua *et al.* [26] used a two-color infrared thermometer to investigate the influence of laser processing parameters on the temperature of molten pool during the laser rapid forming process. G. Bi *et al.* [27] used a single-color pyrometer to study the effect of geometry, power density, and oxidation on the temperature measurement and process control. The dimensional accuracy of the build up was improved in their study. Song *et al.* [28] used a dual-color pyrometer to measure the molten pool temperature and three high-speed CCDs to measure the molten pool height. They achieved a more accurate shape of the finished component by implementing closed-loop control. Most of the work focused on monitoring the fixed-point temperature of the molten pool for feedback. It can improve the geometrical accuracy of the finished component to a certain extent, but does not necessarily result in a uniform molten pool size [29]. A more direct and easier way to control the molten pool size is to monitor the top full-field view of the shape of the molten pool using both video and infrared cameras.

The motivation of this work is to build a sensing and control system for the robotically controlled 8-axis LBDMA system. The system includes sensing and control of the powder flow rate and molten pool size. The

powder flow rate was detected by using the optoelectronic sensor developed at RCAM. An infrared imaging setup was installed on the side of the laser head to monitor the top full-view of the molten pool. A simple proportional integral derivative (PID) controller, combined with the feed forward compensation was used to build a closed-loop control system for the molten pool size. By adjusting the laser power, a uniform molten pool size was achieved during the addition process.

2. Setup of LBDMA System

The schematic and the photo of the LBDMA system is shown in Figs. 1a and 1b. A 4 kW fiber laser with a wavelength of 1070 nm and a laser head connected to the powder delivery system were with a 6-axis robot are the main components of the laser-based direct metal additive system. An additional 2-axis rotatory positioning system was synchronized with the 6-axis robot. During the deposition process, the laser head attached to the robot, was orientated and moved with respect to the support plate fixed at the 2-axis rotary positioning system. When the support plate moved, the laser head would continuously follow the built part without an offset. That significantly simplified the path planning for building complex structures. Fig. 1c shows a propeller printed by the robotized laser-based direct metal addition system. During the addition process, a powder feeder developed by RCAM [5] fed the powder. The optoelectronic sensor monitored the powder flow rate at the outlet of the powder feeder. The design of the powder feeder and the optoelectronic sensor are detailed in Section 3. The stainless steel powder 431L HC sized from 53 to 150 μm that was provided by North America Hoganas High Alloys LLC was chosen as the addition material. The argon carrier gas fed the powder particles into an annular cone nozzle and injected them into the molten pool formed by the laser beam. The shielding gas (argon) was directed through the nozzle toward the molten pool to protect the molten material from contact with the atmosphere. A CCD camera equipped with an infrared filter was installed on the laser head to monitor the molten pool. A fire ware 1394 adapter was used to acquire the infrared images. A PC conducted the image processing and control tasks. The National Instruments PCI-6221 data control board was adopted to control the laser powder and the powder flow rate by sending analog signals to the laser control box and the servomotor of the powder feeder. LabVIEW was used to implement the image processing, control tasks, and the end user interface design.

3. Sensing and Control of Powder Delivery System

A controllable powder delivery system ensures a stable and consistent addition process. The key element for achieving powder delivery control is to detect the powder flow rate in real time. The powder delivery system in RCAM is equipped with a patented powder feeder [5] and an optoelectronic sensor developed for detecting the powder flow rate. As shown in Fig. 2, the powder feeder mainly consists of a hopper, a rotating disk, and a suction device. The hopper stores the powder that is fed continuously at the rotating disk placed under the hopper at a prescribed gap h . Pressurized argon aerates the chamber of the powder feeder. The powder on the disk is continuously sucked out through the suction device due to the pressure difference between the inside of the chamber of the powder feeder and the atmosphere. Given a suitable pressure difference (>10 psi), the powder flow rate is linearly related to the angular velocity of the disk that is controlled by the servomotor. By controlling the rotary speed of the servomotor, the developed powder feeder can achieve a high delivery resolution and a high scalability.

To calibrate the relationship between the powder flow rate and the motor voltage, the motor voltage was changed from zero to 0.5 V with a constant interval of 0.05 V. At each voltage, the motor ran for about 10 seconds before any measurement was taken to ensure a stable powder flow rate. The weight of powder was measured by an electronic scale with an accuracy of 0.001 gram. The powder flow rate at each voltage was determined by measuring the weight of powder delivered during 30 seconds. Such test was repeated three times for each voltage, and the averaged weight was taken to calculate the powder flow rate at the corresponding motor voltage. As shown in Fig. 3, the maximum powder flow rate for the current design of the powder feeder is about 1.2 g/s. The powder feeder exhibits a good linear relationship between the powder flow rate and the motor voltage when the powder flow rate is less than 1.1 g/s. In most LBDMA systems, the powder flow rate is less than 1.1 g/s.

An optoelectronic sensor was developed to detect the powder flow rate at the outlet of the powder feeder. As shown in Fig. 4, the developed optoelectronic sensor consists of a diode laser with a line generator that emits a thin defocused light sheet with a wavelength of 658 nm and power less than 500 mW, a photo diode, a small rectangular glass chamber (6.4 mm wide, 2.2 mm thick and 19.5 mm long), and a set of lenses. The corresponding lens collimates the laser beam in the form of a line before passing through the glass chamber.

Then the laser beam that passes through the glass chamber is focused at the photo diode. Due to diffusion, absorption, and reflection of the powder stream passing through the glass chamber, the amount of light detected by the photo diode would change if the density of powder changes. The photo diode is characterized by a good linearity between the photo energy it detects and the voltage it gives out.

Due to the existence of the measuring white noise of the sensor (see Fig. 7), the acquired voltage signals from the sensor is a discrete-time data set $x(n)$ that is expressed as:

$$x(n) = p + w(n) \quad (1)$$

Where p is the voltage of the sensor (V) corresponding to the actual powder flow rate, and $w(n)$ is the measuring white noise of the sensor (V). In practical measurement process, the averaged result of a set of continuously acquired signal data determines the measured voltage of the sensor in order to decrease the noise disturbance:

$$m = \frac{1}{N} \sum_{n=0}^{N-1} x(n) \quad (2)$$

Where N corresponds to the sampling number of the one-time measurement. This measurement process would result in a measurement time leg determined by:

$$t_{lag} = \frac{N}{f} \quad (3)$$

Where f is the sampling frequency (Hz) of the developed sensor (10 kHz).

First, a set of experiments were conducted to calibrate the developed sensor. The voltage signals of the sensor at different powder flow rates were acquired to build the relationship between the voltage signal of the sensor and the actual powder flow rate. The relationship between the powder flow rate and the motor voltages from zero to 0.5 V with a constant interval of 0.05 V was determined during the calibration process of the powder feeder. Before receiving any data at each powder flow rate, the servomotor ran for about 10 seconds to ensure a stable powder flow. Then the sensor received voltage signals for 30 seconds (Fig. 7 shows a fraction of the acquired signals (1 second)). The sampling number of this one-time measurement is $N = t_{lag} \times f = 3 \times 10^5$. The number was so large that disturbance from the measuring noise became negligible. The averaged voltage m during the 30 seconds represents the output voltages of the sensor at the corresponding powder flow rates (see Fig. 5). The sensor exhibits a good linear relationship between the powder flow rate and the output voltage when the powder flow rate is less than 1.1 g/s (i.e., the linear

delivery range of the powder feeder). A first-order polynomial was used to match the powder flow rates r (g/s) and the output voltages of the sensor h (V). The fitting result is as follows:

$$h(r) = -0.377 \times r + 9.475 \quad (4)$$

The measured powder flow rate from the developed sensor can be used as a feedback to achieve the real-time control on the powder flow rate. As shown in Fig. 6, when the measured powder flow rate deviates from the preset value, the motor voltage is adjusted to track the preset powder flow rate. A small measurement time lag is needed essentially for the developed sensor when used in the real-time control system of the powder flow rate. With a higher sampling number N , the error between the measured result and the actual powder flow rate is smaller (see Equations (1) and (2)), but it would result in a longer time lag (see Equation (3)). In this study, a stable measurement of the powder flow rate was defined to be achieved if the errors between the measured powder flow rate and the actual powder flow rate were kept less than a prescribed value δ (g/s):

$$|r(m) - r(p)| < \delta \quad (5)$$

δ is determined based on the requirement of the measurement accuracy. r is the inverse function of Equation (4) that is used to calculate the powder flow rate after the voltage of the sensor is obtained.

$$r(h) = -2.653 \times h + 25.133 \quad (6)$$

h is the voltage of the sensor (V). $r(h)$ is the corresponding powder flow rate (g/s).

To achieve a stable measurement of the powder flow rate defined as Equation (5) with a minimum time lag, the voltages of the sensor acquired at motor voltage of 0.05 v for one second (see Fig. 7) were used to determine the suitable sampling number of one measurement N . $r(p)$ was the actual powder flow rate at the motor voltage of 0.05 v that was determined during the calibration process of the powder feeder (0.216 g/s). The maximum measuring errors $|r(p) - r(m)|$ under different sampling numbers N (from 5 to 300) were calculated. The results in Fig. 8 show that the measuring error becomes smaller with a larger sampling number N . In this study, the measurement accuracy δ was set at 0.005 g/s . $N = 200$ met Equation (5) with a safety margin. The corresponding measured voltages of the sensor and the powder flow rates for this one second were calculated based on Equation (6). The measuring errors of $\pm 0.004 \text{ g/s}$ (see Fig. 9) achieved the stable measurement defined in Equation (5). For the developed sensor, the stable measurement

with an accuracy of $0.005g/s$ was achieved with a sampling number N of 200. The corresponding time lag was 20 ms when used for the real time control of the powder flow rate.

4. Sensing and Closed-loop Control of Molten Pool Size

Sensing and control of the molten pool size has a significant effect on the geometrical accuracy of the finished buildup, its microstructural properties, and the bonding between layers. In this study, an infrared imaging setup was installed at the laser addition head to monitor the molten pool size. It included a high frame rate CCD camera, an infrared filter (>695 nm), an iris, a set of optical mirrors that were used to guide the light from the molten pool into the CCD chip of the camera, and an infrared notch-filter that blocked the laser light with a wavelength of 1070 nm. The high frame rate CCD camera was installed at the side of the laser head (see Fig. 1a). With the help of the set of optical mirrors, a top full-field view of the molten pool was acquired. Due to the presence of the powder above the molten pool, the acquisition of the video image of the molten pool was disturbed and the contour of the molten pool could not be detected accurately. An infrared filter was installed in front of the camera to eliminate the issue of the powder presence above the molten pool. The calibration of the infrared image is based on the coaxially captured video image which is more direct and reliable compared to the work shown in [6, 18], where infrared image was calibrated by using a black body. In this study, both the video and infrared camera under the same scanning conditions acquired coaxially the images of the referenced molten pool without powder. Since the contour of the molten pool is determined by the melting temperature of the corresponding material, the emissivity along the contour of the molten pool is uniform. Based on Planck's law, a particular grayscale contour (isotherm) on the infrared image could represent the actual contour of the molten pool. To determine the isotherm on the infrared image that corresponded to the contour of the molten pool. the images from video and infrared cameras were overlapped. Fig. 10a shows the infrared image of the molten pool when scanning the substrate without powder (laser power: 400 W, scanning speed: 20 mm/s). The resolution of the infrared image was 320×240 pixels. The video image of the molten pool under the same scanning conditions was also captured coaxially by replacing the infrared filter with a band pass optical filter (532 nm) and illuminating the molten pool by a green laser (532 nm) at a power of 5 W. As shown in Fig. 10b, the contour of the molten pool in video image is clear. By overlapping the video image over the infrared one, the contour of the molten pool

on the infrared image can be determined by the isotherm with a specific value of a gray level. In this case, the gray level of 97 on the infrared image represented the contour of the molten pool (see Fig. 10c).

To verify the accuracy of the gray level determined by the proposed calibration approach, a set of scanning tests with different scanning conditions (scanning speed: 0.02 mm/s, 0.03 mm/s, 0.04 mm/s; laser power: 400 W, 600 W, 800 W, 1000 W, 1200 W, 1400 W) were conducted without powder. The corresponding video images and the contours of the molten pools on the infrared images with gray level threshold of 97 are shown in Fig. 11. The shapes of the molten pools extracted from the infrared images had a high similarity with the actual shapes of the molten pools obtained from the video images. Also, as a representation of the width of the actual molten pool, the widths of the heat mark on the substrate w (see Fig. 10d) after the laser scanning under different conditions were measured. The results are shown in Fig. 12a for a comparison with the widths of the extracted molten pools at the infrared images. The obtained results matched well with an acceptable error of ± 0.1 mm (see Fig. 12b). The length and area size of the extracted molten pools from the infrared images are also shown in Fig. 12. Generally, all of the three parameters could be used separately as a controlled variable to achieve a stable molten pool. For an online control process, measuring the area size of the molten pool is preferred for extra computational cost is needed to calculate width and length of the molten pool, which would aggregate the delay in an online control process. By adjusting the laser power based on the measured molten pool size, a uniform geometry of the buildup could be achieved during the addition process.

To achieve a uniform molten pool size during the addition process, the infrared image acquisition system took images of the molten pool in real time. The pixel number inside the molten pool was used as the feedback signal into the control system of the molten pool size. In this study, a simple PID controller was adopted to build the closed-loop control system. Due to the existence of time lag (less than 70 ms) in the control loop (to acquire the image, process the image, and send the analog signal to the laser control box), a feed forward compensation was introduced for the control of the molten pool size. The schematic of the control system is shown in Fig. 13. The continuous control equation can be expressed as

$$u(t) = K_p e(t) + K_i \int e(t) dt + K_d \frac{de(t)}{dt} + K_f A_m(t) \quad (7)$$

Where K_p is the proportional gain, K_i is the integral gain, K_d is the derivative gain, and $e(t)$ is the error

defined by $e(t) = A_p(t) - A_m(t)$. Where $A_p(t)$ is the preset size of the molten pool (pixel number), and $A_m(t)$ is the measured size of the molten pool (pixel number). $A_a(t)$ is the actual size of the molten pool (mm^2). K_f is the feedforward gain. $u(t)$ is the analog signal (V) sent to control the laser power. The analog signal ranges from zero to 10 V and corresponds to laser power from zero to 4 kW. To implement the algorithm for the control of the molten pool size in the computer, Equation (7) is further discretized as

$$u(k) = K_p e(k) + K_i T \sum_{i=0}^k e(i) + K_d \frac{(e(k) - e(k-1))}{T} + K_f A_m(k) \quad (8)$$

by replacing the integral with the sum of the errors in the previous k steps and replacing the derivative with first order backward difference of the error between *step k* and *step k - 1* (*step k* is the current step). $u(k)$ is the analog signal (V) sent to control the laser power at *step k*. $e(i)$ is the error between the preset molten pool size at *step i* and the measured molten pool size at *step i*. T is the processing period. In this study, the image acquisition and its processing rate was 12 frames/s during the building process. So T was determined to be $\frac{1}{12}$ s.

To build a complex geometry, the deposition points which need special attention generally include starting points, direction-turning points and ending points. L-shaped single-beam wall which includes all of those points was chosen as the building target to test the performance of the closed-loop control system. Two L-shaped single-bead walls were built without and with closed-loop control, respectively. The sequence of the addition path is shown in Fig. 14. The L-shaped single-bead wall (two segments were both 20 mm long) was built at a corner of the square substrate (110 mm wide, 110 mm long, and 3 mm thick). The laser head was moved from one ending point to the other one to build one layer, then it was lifted up for an increment along the height direction (z-axis) and continued to build the next layer following the same path in the reverse manner. The solid red line indicates the path segments in which the laser power shutter was on. When the nozzle came to the path segment denoted by dashed-line, the laser power was turned off. The scanning parameters are shown in Table 1.

First, a 40-layer single-bead L-shaped wall was built without the closed-loop control. The laser power was set at 400 W during the whole building process. Fig. 15 shows the infrared images of the molten pools and the corresponding contours and sizes of the molten pools. It is clear that the molten pool size varied significantly at different locations. Position 1 and position 5 were at the ends of the layer where the heat

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5 conduction was limited to one side of the built wall. So the molten pool was relatively larger than in the
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7 position far from the ends, resulting in higher buildups (see Fig. 18a). Wider beads at two ends of the
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9 finished part were achieved (see Fig. 18b). The molten pool at position 3 where the laser addition head
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11 changed the direction of motion (90^0) was also larger than at the other positions due to the deceleration of
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13 the robotic arm. Since the nozzle stayed at the turning point relatively longer with the continuous powder
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15 feeding, a buildup was formed at this point (see Fig. 18a). Buildup is a common problem during the
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17 manufacturing of complex parts by LBDMA when the direction of motion changes. Fig. 16 shows the
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19 variation of the molten pool size along two adjacent built layers. During the manufacturing process, the
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21 segment 1-2-3 (3-2-1) was located along the edge of the substrate where the heat conduction was limited to
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23 one side of the substrate (see Fig. 14). The molten pool size was relatively larger than at segment 3-4-5
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25 (5-4-3). After the addition of segment 3-4-5, the laser power turned off, and the addition head was lifted up.
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27 Due to the cooling during this period, the molten pool size of segment 5-4-3 was smaller than that of
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29 segment 3-4-5. Fig. 17 displays the molten pool size during the entire addition process. At the beginning of
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31 the building process, the substrate acted as a heat sink. Only a fraction of the laser energy was used to form
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33 the molten pool. Consequently, the size of the molten pool was smaller near the substrate, which led to a
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35 narrower bead width at the bottom of the L-shaped single-bead wall (see Fig. 18c). As the wall grew, the
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37 heat conduction at the substrate became less. Thus, the bead became wider until it reached a thermal
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39 equilibrium.

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41 The same addition process was conducted with the closed-loop control system that was developed for the
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43 molten pool size. In this control system, the actual molten pool size $A_a(k)$ would track the preset molten
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45 pool size $A_p(k)$ (see Equation 8). In the test without control, the molten pool size varied from 6000 to
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47 17000 pixels (0.77 mm² to 2.18 mm²). To obtain a comparative size of molten pool in the test with control,
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49 the registered molten pool size was set at 12000 pixels (1.54 mm²). The tuning of the PID controller was an
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51 integrated, interactional and empirical process. Repeated trials were important and necessary before
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53 achieving a desirable performance. Some basic rules could be found in [30]. Table 2 shows a set of PID
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55 parameters which exhibited a good performance in this study.

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57 Figs. 19a and 19b show the trend of the molten pool size and the laser power during the whole addition
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59 process, respectively. At the beginning of the building process with control, the laser was turned on to a
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5 preset power of 400 W. Then the first infrared image was captured in 0.083 s, the PID controller compared
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7 the detected molten pool size (around 6000 pixels) to the preset molten pool size (12000 pixels) and sent a
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9 signal to the controller of laser power to increase the power to around 550 W to compensate for the heat sink
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11 effect of the substrate, resulting in the increase of the size of molten pool (to 12000 pixels) as shown in Fig.
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13 19. Figs 17 and 19 have the same starting points, but it is hard to notice that due to a short period of time
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15 (0.083*2 s). Then, the laser power was gradually decreased to 370 W until a thermal equilibrium was
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17 reached. Figs. 20a and 20b shows the zoomed-in variation of the molten pool size and laser power for the
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19 two adjacent built layers. Peaks of the molten pool size at the ends of the layers and at the point where the
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21 direction of motion changed decreased due to the action of the closed-loop control system. The built wall
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23 with a closed-loop control system is shown in Fig. 21. A uniform geometry was achieved in both the vertical
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25 and horizontal cross sections. There was no buildup at the ends and the change-of-direction point. The
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27 developed closed-loop control system of the molten pool size exhibited a good performance in achieving
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29 uniform buildup geometry by using LBDMA.
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31 32 **5. Conclusions**

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34 A sensing and control system for a robotically controlled 8-axis LBDMA system was developed in this study.
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36 It includes sensing and control of the powder flow rate and molten pool size. The powder flow rate under the
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38 powder feeder was detected by the optoelectronic sensor developed by RCAM. This sensor exhibited a good
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40 linear relationship between the powder flow rate and the output voltage of the sensor. It is the main
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42 component in the on-line control system of the powder flow rate in a LBDMA system. An infrared imaging
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44 setup was installed on the laser head to monitor the top full-field view of the molten pool. The contour of
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46 molten pool at the infrared image was determined by overlapping it with the video image obtained without
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48 the presence of powder. It was verified that the calibrated contour of the molten pool at the infrared image
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50 could accurately represent the actual molten pool shape. A simple PID controller, combined with feed
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52 forward compensation was adopted to build a closed-loop control system for the molten pool size. Two
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54 L-shaped single-bead walls were built with and without control, respectively. The buildups at ends,
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56 change-of-direction point, and the inconsistent bead widths were eliminated by using the closed-loop
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58 control.
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Figure Captions

Fig. 1 Setup of the LBDMA system: (a) schematic, (b) photo, (c) printed propeller at the LBDMA system

Fig. 2 Powder feeder

Fig. 3 Relationship between the motor voltage and the powder flow rate

Fig. 4 The optoelectronic sensor: (a) schematic, (b) photo

Fig. 5 Relationship between the powder flow rate and the averaged sensor voltage

Fig. 6 Flow chart of the sensing and control of the powder flow rate

Fig. 7 Voltages of the sensor acquired at motor voltage of 0.05 v for one second

Fig. 8 Maximum measuring error with different sampling numbers N

Fig. 9 (a) Measured voltages of the sensor, (b) measured flow rates, and (c) the measuring errors with sampling number N=200

Fig. 10 Captured top full-field images under same scanning conditions: (a) infrared image, (b) video image, (c) the contour of the molten pool on infrared image, (d) heat mark on the substrate

Fig. 11 Video images and the contours of molten pools on the infrared images under different scanning conditions

Fig. 12 Geometry of the molten pool under different scanning conditions without powder: (a) width of the molten pool extracted on the infrared images and measured from the heat marks, (b) error between the two kinds of width in (a), (c) length of the molten pool extracted on the infrared images, (d) area of the molten pool extracted on the infrared images

Fig. 13 Schematic of the closed-loop control system

Fig. 14 Schematic of the addition path

Fig. 15 Shape and size of the molten pools at different deposition positions (unit of the molten pool size: pixel number (mm²))

Fig. 16 Molten pool size of two adjacent built layers without control

Fig. 17 Molten pool size (pixel number) of the whole building process without control

Fig. 18 “L” shape single-bead wall without control of the molten pool: (a) photo (the sample shown here was cut from the original substrate shown in Fig. 14), (b) horizontal cross-section of buildup, (c) vertical cross-section of buildup

Fig. 19 (a) Molten pool size (pixel number) and (b) laser power variation of the whole building process with control

Fig. 20 (a) Molten pool size (pixel number) and (b) laser power for building two adjacent layers with control

Fig. 21 “L” shape single-bead wall with control of the molten pool size: (a) photo (the sample shown here was cut from the original substrate shown in Fig. 14), (b) horizontal cross-section of buildup, (c) vertical cross-section of buildup

Table Captions

Tab. 1 Deposition parameters for building “L” shape single-bead wall

Tab. 2 Parameters of the PID controller for building “L” shape single-bead wall with control

(a)

(b)

CAD model

Printed component

(c)

Fig. 2

Fig. 3

Fig. 4

Fig. 5

FIG 6

Fig. 7

Fig. 8

Fig. 9

Fig. 10

Fig. 11

Fig. 12

(a)

(b)

(c)

(d)

Fig. 13

Fig. 14

Fig. 15

Fig. 16

Fig. 17

Fig. 18

Fig. 19

Fig. 20

Fig. 21

TABLES

Parameter	Scanning speed (mm/s)	Laser power (W)	Molten pool size (pixel (mm ²))	Powder feed rate (g/s)	Carrier gas (L/min)	Shielding gas (L/min)	Z increment (mm)
Without control	5	400	(Fig. 17)	0.45	7.05	11.75	0.3
With control	5	Automatically adjusted (Fig. 19-b)	Preset: 12000 (1.54)	0.45	7.05	11.75	0.3

Tab. 2

k	K_p	K_i	K_d	K_f	$T(s)$
4	1.3×10^{-4}	0.014×10^{-4}	0.04×10^{-4}	0.76×10^{-4}	0.0833