Study of Forming Efficiency by Real-time Correction of Head Nozzle Height in Directed Energy Deposition

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Abstract. Laser metal deposition is of two types: powder bed and metal deposition. Either method is expected to be a breakthrough in innovative design and manufacturing technology development because both methods can form shapes that cannot be formed by conventional removal processing. One metal deposition method is directed energy deposition (DED), in which a laser irradiates the target position on the metal layer to melt it, and metal powder is supplied to the target position to perform molding. DED is expected to produce large parts and repair molds. However, as the lamination mechanism is not sufficiently clarified, relationships between process parameters, material properties, molding accuracy, and molding efficiency are not clear, making stable molding difficult [1]. One obstacle to stable molding is that the distance between the head nozzle that supplies the metal powder and the molten pool cannot currently be kept constant. In this study, we measure the distance between the head nozzle and the molten pool using a triangulation method, propose a method to control the position of the head nozzle to keep the distance constant, and experimentally verify the method’s usefulness.

1. Introduction

In additive manufacturing (AM), design and manufacture can be used continuously and integrally based on three-dimensional (3D) data, because the object is formed using digital data of the object structure created by 3D computer-assisted design (CAD) or computer graphics (CG). As a result, it is possible in principle to produce a target object while minimizing both the amount of materials and the number of processes, and in recent years this approach has attracted attention as a way to manufacture at low cost and with low environmental impact. AM encompasses several methods. Among them, the method of using a laser and a metal material is generically referred to as laser metal deposition. One metal deposition method is directed energy deposition (DED), which attaches a laser head device and a powder supply device to a machine tool and performs laminating. DED is a multidisciplinary technology that uses laser technology, CAD/CAM, robotics, sensors, controls, and powder metallurgy. However, the final characteristics of parts fabricated by DED depend on various process parameters such as laser power, powder mass flow rate, scanning rate, carrier gas flow rate, and shield gas flow rate. Therefore, many studies have focused on technical performance such as hardness, wear resistance, phase analysis, and corrosion resistance of parts molded using DED [2],[3],[4],[5].

In order to obtain the desired geometrical dimensions and material properties in a finished product, it is important to control the process parameters. Many researchers are currently examining the relationship between process parameters and the sedimentary layer. Choi et al. studied the influence of process parameters on the thickness of the deposited layer and reported that setting the powder mass...
flow rate and the thickness per layer is critical to minimizing the difference between the preset layer height and the actual layer height [6]. In response, Do-Sik Shim et al. developed a process diagram for correlating the setting of the layer height and process parameters, and proposed a layer thickness setting method that was adapted to various processes [7]. This also revealed the influence of process parameters on material properties. Ruan et al. studied the empirical relationship between deposit height and laser scan rate under a constant laser power and powder feed rate [8]. However, as this empirical model only works under specific process conditions, the predicted deposit height results are not accurate when the experimental conditions are changed. Therefore, Ehsan Toysr et al. proposed a method of installing an optical charge-coupled device (CCD) sensor and performing feedback control in real time according to various experimental conditions by controlling the laser output using a pattern recognition algorithm [9]. However, as described in Do-Sik Shim et al., this method changes parameters that affect material properties such as the laser power and powder mass flow rate, so that the method may not yield an optimally shaped object [7].

Therefore, this study aims to not only improve the dimensional accuracy of the 3D metal lamination molding machine but also control the lamination height in real time without changing process parameters that affect material characteristics. The distance between the tip of the laser head and the molten pool (also called the standoff distance) causes an error with the input ideal distance as the number of layers increases. In this study, the height of the laser head nozzle is controlled in real time as the number of layers increases so that the height of the formed object is controlled. In order to observe the molten pool in real time, it is necessary to install a small camera on the head, so a jig for camera installation was constructed. We photographed the molten pool with the camera, and using the results of analyzing the captured image, the model was formed while correcting the head nozzle height as the number of layers increased. Finally, in order to confirm the usefulness of our modifications, we compared a product produced with this method to one produced by the conventional stacking method.

2. Control Method of Head Nozzle

2.1. Modeling Method by DED

In the DED method shown in Figure. 1, laser irradiation from the head nozzle is used to melt and stack the powder. A portion of the object to be shaped is irradiated with a laser to form a molten pool, toward which a metal powder is discharged together with a carrier gas (Ar) from a nozzle coaxial with the laser, and the head nozzle is moved in the laminating direction to perform lamination. The head nozzle also supplies shielding gas (Ar) that prevents air from entering into molten pool.

In order to increase the number of stacks, the head nozzle height is input to the 3D printer in accordance with the stacked height for each one-layer stack in the DED method. In conventional DED, the head nozzle height adjustment has been a constant value for each lamination cycle. As the number of lamination cycles increases, the difference between the height of the actually formed laminate and the ideal height calculated by the target parameters becomes larger. In other words, there is an error when comparing the dimensions of the finished object with the target dimensions.

2.2. Method for Measuring the Distance Between the Head Nozzle and the Molten Pool (Standoff Distance: SOD)

In this study, a camera is mounted on the head nozzle, and the distance between the head and the molten pool (SOD) is measured by triangulation from the image taken by the camera. Figure. 2 shows the positional relationship between the camera mounted on the head nozzle and the molten pool. From the laser irradiation angle and the camera position, the displacement x from the reference position of the molten pool can be calculated from Eq. 1.

\[ x = \frac{dD}{f \sin \theta + d \cos \theta}. \]  

From Figure. 2, the distance between the head nozzle and the centerline of the camera is \( A \) [mm], the distance between the center of the camera and the top of the molten pool is \( D \) [mm], and the angle
between the head nozzle and the center of the camera is \( d \) [mm], and the molten pool displacement from the camera is \( x \) [mm]. \( A, D, \theta, \) and \( f \) are all fixed values. From Eq. 1, it can be seen that SOD is a curve for the shift of the molten pool in the camera head. Although the displacement \( x \) can be calculated from Eq. 1, when the displacement \( x \) is calculated from the position \( d \) of the molten pool in the camera image, the accuracy is reduced due to the camera position error and the irradiation angle error of the laser. Therefore, in this study, the relationship between displacement \( x \) and position \( d \) was acquired as calibration data, and displacement \( x \) was determined from position \( d \).

Next, the method of acquiring calibration data is explained. First, we input the image (Figure. 3) taken by the camera into Python. Python can be used to transform the coordinate system with \( x \) [pixel] in the image and \( y \) [pixel] in the vertical and extract the coordinate system constructed by the image name and the RGB value of each coordinate. Furthermore, only specific RGB value ranges are extracted from the linked coordinate values. In this study, only the coordinate values for (R, G, B) = (255, 255, 255) are extracted. To obtain the center of the molten pool from the extracted coordinate values, it is assumed that the molten pool is a circle, with the \( y \)-axis being constant [10]. Finally, the location where the range of \( x \) is the largest is identified, and this midpoint is designated as the molten pool center. A calibration curve and standoff distance (SOD) can be obtained by plotting the molten pool center coordinates. The calibration curve can be approximated as a straight line because the value of \( d \) is sufficiently small.

The resolution \( p \) [mm/pixel] of the correction value \( x \) [mm] input to the laser layered metallurgical modeling machine can be obtained from Eq. 2 whenever the \( 1 \) [pixel] molten pool coordinate value changes.

\[
p = \frac{x}{d}, \tag{2}
\]

Where \( d \) [pixel] now is the change of the molten pool coordinate value in the image when the displacement of the molten pool changes \( x \) [mm].

2.3. How to Determine SOD

The displacement \( x \) from the reference position of the molten pool can be calculated by the above method. Since the optimal value of displacement \( x \) is 0, correction control is performed on the \( Z \) value (the value to be input to the 3D printer) of the formation path so that the displacement \( x \) becomes 0 when forming the layer above it.

3. Experimental Procedure

3.1. DED Processing Conditions

In this study, a shaped object of Inconel 625, a nickel-based heat-resistant alloy was fabricated using a laser metal forming and milling processing machine (LaserTec 65 3D, DMG Mori Co., Ltd.) as shown in Figure. 4. The experimental conditions such as SOD, laser power, and scanning speed were input to the multitasking machine by the NC program. The stacking conditions other than SOD are not changed. Regarding the measurement of the object, the shape of the object was reproduced using a Nikon P3D NC-2323S measuring system. Table 1 shows the experimental conditions. The VICOCO camera
mounted on the head nozzle has a size of is 24 mm long, 26 mm wide, and 20 mm deep. The maximum resolution of the camera is $2.0 \times 10^6$ [pixel].

3.2. Acquisition of Calibration Date
The combined processing machine used in this study has an SOD reference value of 11 mm when performing the first layer of lamination, and it increases by 0.4 [mm] for every layer following. The calibration data were acquired by changing the SOD of the first layer from 9 [mm] to 13 [mm]. The relationship between the molten pool position $d$ of the image taken with the camera and the SOD is as shown in Table 2, and the resolution in this study was determined to be $p = 0.049$ [mm / pixel].

3.3. Experiments Using the Correction Method
In experiments using the correction method, it is assumed that the position $d$ of the molten pool is derived in real time; based on that, the displacement $x$ of the head nozzle is also corrected and controlled. However, in this experiment, calculation of the position $d$ and correction control of the displacement $x$ could not be performed in real time because of the equipment, so after four layers were formed, the calculation of the position $d$ and correction control of the displacement $x$ was done manually, and the operation was repeated to form a single line of 25 [mm] up to 40 layers. In addition, in order to confirm the usefulness of this method, 40 layers of 25 [mm] in a single line were formed without correction control of displacement $x$ (e.g., every time one layer is stacked, raise the nozzle by 4 [mm]).

3.4. Verification of the Experimental Results and the Usefulness of the Proposed Method
Figure 5 shows the results of additive manufacturing with and without correction control of displacement $x$. The measurements of the cross section of the resulting shaped object are shown in Figure 6. The model with correction had a height of 28.84 [mm], and the model without correction had a height of 20.26 [mm]. From this, it was confirmed that the correction control improves the shaping efficiency by 40%.

Figure 7 shows the difference from the optimum value (11 mm) of the distance between the head nozzle and the molten pool with and without correction control. As shown in the figure, it can be seen that the correction control is optimally set at the corrected stage. That is, in the proposed method, the Z coordinate value of the head nozzle is known, and the distance from the head nozzle to the molten pool

| Deposition Condition | Value |
|----------------------|-------|
| Laser power [W]      | 2,000 |
| Feed rate [mm/min]   | 500   |
| Powder flow [g/min]  | 14    |
| Carrier Gas [l/min]  | 6     |
| Shield Gas [l/min]   | 5     |
| Powder material      | Inconel 625 |
| Powder size [μm]     | 53~150 |
| Base plate           | S45C  |
is maintained at 11 mm. Therefore, it is possible to perform molding knowing the height of the object. In this study, the moving distance of the head without correction was 16 [mm] (optimal modeling height) because 40 layers were laminated with 0.4 [mm] per layer, and the error rate with the actual object was 21%. The movement distance of the head with correction was 28.67 [mm] (optimal modeling height) as a result of changing 4 of the 40 layers, and the error rate with the actual object was 0.49%.

These results demonstrate that the proposed method can accurately mold an object with improved molding efficiency compared to conventional DED. Also, as can be seen from Figures. 5 and 6, the

Table 2 Molten pool coordinate values for head nozzle height change

| SOD (Standoff Distance) [mm] | 9   | 10  | 11  | 12  | 13  |
|------------------------------|-----|-----|-----|-----|-----|
| Molten pool coordinate value [mm] | 967 | 982 | 989 | 1001| 1013|

Figure. 5 Modeling results

Figure. 6 Measurement results

Figure. 7 Difference between SOD and optimum distance

width of the shaped object with correction was constant compared to the width of the shaped object without correction. This is because SOD was kept constant. Therefore, the proposed method’s usefulness is confirmed (Figure. 7).

4. Conclusion

In this study, we propose a method of stable formation in DED and a method to keep SOD constant by monitoring the molten pool with a camera mounted on the head nozzle, and we compare the results of both methods experimentally. The proposed method is useful and forms an accurately shaped object with improved molding efficiency.
In future studies, we will improve the accuracy of the camera, fully automate the modeling method by inputting automatically corrected Z values for each layer, add the sensor function for measuring the molten pool temperature to the camera, and stably model the modeled object.

5. References

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