1. Introduction

In recent years, Additive Manufacturing (AM) has attracted great attention in various industries. In particular, laser metal deposition, which is one of AM processes, is highly expected in aerospace and heavy electric industries (Kakinuma et al., 2016), (Zhong et al., 2015).

Subtractive machining for a complex-shaped part has various issues: more than 90% of material is removed and disposed of during machining; and a part may need to be divided due to limitation of machining forms.

Against these backgrounds, there has been increased attention to hybrid machine tools that combine subtractive and additive techniques because of their superior capability of producing highly complex-shaped metal parts. Directed Energy Deposition (DED) has a great applicability to the production of complex-shaped metal parts. DED machine is constructed by mounting a laser and powder supply device on a machine tool and can produce relatively large parts, compared with Powder Bed Fusion (PBF) (Kyogoku, 2016).

DED of metal material has been studied recently in AM field, and it was found that voids generated in the deposited metal material cause deterioration of mechanical strength. Therefore, void avoidance is one of the important issues to achieve a higher level of strength in the DED process (Koike et al., 2016), (Ashida et al., 2017).

In this study, Inconel 718, which is frequently employed for machine components in aerospace and heavy electric industries, was used for metal deposition, and the mechanism of void generation was investigated through the dynamic observation by high-speed camera, the thermal observation by the two-color temperature measurement, and the evaluation of the porosity. The experimental result shows that solidification time has an influence on the void generation.
2. Principle and issue of DED

2.1 Principle of DED

Figure 1 shows principle of metal deposition in the DED method. While laser is irradiated from the center of nozzle, metal powder is supplied from the nozzle with carrier gas to the molten pool. The supplied metal powder is deposited by melting and solidifying. To protect the optical system, the shielding gas is supplied as well. Argon gas is used for both carrier gas and shielding gas. The distance between nozzle and base plate is 11 mm, the diameter of nozzle hole size is 4.6 mm.

![Fig. 1 Principle of DED](image)

2.2 Void generation of DED

Voids often appear in the deposited part in DED. Figure 2 is an optical microscope photograph showing the cross section where one layer is deposited on a base plate and some voids are generated.

![Fig. 2 Cross-sectional image of deposited metal part](image)

3. Experimental device and method

3.1 Experimental device

Figure 3 shows the hybrid machine tool LASERTEC 65 3D produced by DMG MORI that was used in the experiment, which can conduct DED process and cutting process sequentially. The stage can be both tilted and rotated and the laser nozzle moves in the X, Y, and Z axes, enabling three-dimensional deposition. Machining process is also possible by changing the laser nozzle to a cutting tool. Regarding laser, the top hat type is employed to achieve uniform energy distribution. The laser transmitter LMD2500-60 produced by LASERLINE, which laser spot diameter is 3 mm and the wavelength is 980 nm.

![Fig. 3 DED of Inconel 718](image)
3.2 Experimental method

3.2.1 Dynamic observation by high-speed camera

To visualize the dynamic movement of powder and molten pool during deposition, a high-speed camera was used. However, the clear observation on the deposition was difficult due to the high intense laser beam as shown in Fig. 3. To solve this issue, the band pass filter was used to cut off the wavelength of 980 nm and the additional 640 nm laser beam was irradiated. Figure 4 and 5 show the schematic of observation system and its appearance.

3.2.2 Thermal observation by two-color temperature measurement

Thermal distributions were observed by the two-color temperature measurement which is built-in the high-speed camera. The principle of the two color measurement is that the ratio in the two wavelengths of radiation energy varies almost proportionally to the temperature. Hence, This method is not affected by emissivity (Usui and Mitsui, 2010). The high-speed camera is calibrated using a tungsten light bulb as temperature standard. After taking the movie by the high-speed camera, the raw image was processed by two-color temperature method. The measurable ranges of temperature are set from 1,000 °C to 1,900 °C and 1,300 °C to 2,100 °C. As the display temperature range of the processed image is limited to 400 degrees, the image temperature range is set from 1,200 °C to 1,600 °C and from 1,700 °C to 2,100 °C, in order to visually investigate melting and solidifying of deposited part and behavior of molten pool, respectively. Figure 6 (a) shows the raw image, (b) shows the processed image which is low range 1,200 °C to 1,600 °C and (c) shows high range 1,700 °C to 2,100 °C.

According to figure (c), the metal is sufficiently melted because the temperature is clearly over melting point 1,346 °C of Inconel 718. In this study, low range is used to measure the time interval from melting to solidifying. Thus, the vicinity where laser is irradiated in the low range, i.e. the area where the temperature is higher than the measurable range, appears in black.
To measure the time interval from melting to solidifying, thermal measurement points A and B are set as shown in Fig. 7. Although the time interval would be measurable by observing the temperature continuously at a certain point on the scanning path, the shape of molten pool looks like tilted ellipse in the image due to observation in oblique direction and deposition thickness. Therefore, the time interval measurement was conducted by setting two measurement points, whose phase lag is largest, on a certain vertical line. The points A and B are set on the same vertical line; Point A gets higher temperature earlier than the other points, and Point B remains temperature later than the other points. By comparing the melting time at the point A and solidifying time at the point B, the time interval is calculated as shown in Fig. 8 in this study.
3.2.3 Deposition with different laser output and number of layers

To investigate how the porosity is affected when the laser output is changed, the deposition process was performed with three different outputs—1,280 W, 1,600 W, and 2,000 W—without changing other parameter settings.

To investigate the influence of the number of layers, three different numbers of layers—1, 2, and 21-layer—were deposited. 2-layer is to investigate re-melting of 1-layer and 21-layer is decided by maximum layers for consideration of high-speed camera installation. Figure 9 shows the deposited test piece with the laser output of 2,000 W.

The length of deposition track was 50 mm, and the layers were deposited on the same base plate. Table 1 shows deposition conditions for this experiment.

The deposition tests were shot under all deposition conditions respectively by the high-speed camera, and the temperature distributions were observed by the two-color temperature measurement. In the case of depositing 2-layer and 21-layer, a constant interval of 15 minutes was secured from the previous deposition.

The powder used in the experiment was Inconel 718 whose melting point is 1,346 °C and solidifying point is 1,329 °C. Table 2 shows the powder characteristics.

For porosity analysis, the deposited parts were cut at positions A, B, and C as shown in Fig. 10. After that, the cut surface was polished and observed by an optical microscope. The porosity was calculated by the view with binarization processing. The porosity is the ratio of the black area in the deposited part. Figure 11 shows the microscope observation view and image for area where the porosity was calculated.

Table 1. Deposition condition

| Laser output [W] | 1280 | 1600 | 2000 |
|------------------|------|------|------|
| Feed rate [mm/min] | 1000 | 1000 | 1000 |
| Energy density [J/mm²] | 25.6 | 32.0 | 40.0 |
| Powder flow [g/min] | 14 | 14 | 14 |
| Carrier Gas [l/min] | 6 | 6 | 6 |
| Shield gas [l/min] | 5 | 5 | 5 |
| Number of layers | 1 | 2 | 21 |
| Base plate | S50C | S50C | S50C |

Table 2. Powder characteristics

| Material | Inconel 718 |
|----------|-------------|
| Melting point | 1346 °C |
| Solidifying point | 1329 °C |
| Particle size [µm] | 53 ~ 150 |

Fig. 9 Deposited part with 1, 2, and 21-layer

Fig. 10 Deposited part and point of section

Fig. 11 Image observed by microscope
4. Experimental result

4.1 High-speed camera observation

Figure 12 shows the image shot by the high-speed camera during the deposition processes for different numbers of layers with different laser outputs. It was figured out that the molten pool was located under the laser nozzle center and metal powder supplied with shielding gas and carrier gas hitting the molten pool caused waves in the molten pool structure. Thus, the gas seems to enter the molten pool and remains as voids.

Moreover, as the laser output increased, the molten pool size became larger. For example, at the first layer, with the laser output of 1,280 W, the molten pool size was 2.4 mm; with 1,600 W, 2.7 mm; and with 2,000 W, 3.0 mm.

While 2-layer was being deposited, 1-layer was melted again. Particularly with the laser output of 2,000 W, the molten pool depth reached to the vicinity of the boundary of the base plate.

At the 21-layer, the previously deposited layers were melted again, and with 2,000 W, the molten pool eroded to the side of the deposited wall.

Fig. 12 Deposited part and point of section

![Image of deposited part and point of section]
4.2 Thermal observation

Figure 13 shows the observation images of deposition at different layer with different laser outputs acquired by the two-color temperature measurement.

After Inconel 718 was melted, it is naturally cooled down. As the result, the cooling area looked like a tail fin. As the laser output increased, the tail fin became longer and the solidification time $\Delta t$ became longer.

The tail fin also became longer as the number of deposited layers increased. This is due to either of the following reasons:

- The distance from the base plate with a large heat capacity to the deposited area became longer and heat easily accumulated.
- The interval from the previous deposition process was not long enough for cooling as only 15 minutes

![Image showing thermal observation at different laser outputs and deposition layers](image-url)

Fig. 13 Image shot by high-speed camera
Figure 14 is the graphs showing thermal distribution between the nose (point A) and the tail (point B) while different numbers of layers were deposited with different laser outputs.

(a). 1-layer

(b). 2-layer

(c). 21-layer

Fig. 14 Time intervals from melting to solidifying
Although some noise and spatters were detected, the solidification time $\Delta t$ was calculated approximately. Figure 15 shows the solidification time for different conditions of the laser output and the number of layers. While 1-layer is deposited with a laser output of 1,280 W, $\Delta t$ was 0.25 seconds; with 1,600 W, 0.28 seconds; and with 2,000 W, 0.32 seconds. The result indicates that when the laser output increases, the solidification time becomes longer.

![Figure 15 Comparison of $\Delta t$](image)

### 4.3 Comparison with porosity and time interval from the melting point to solidifying point

The deposited parts with each condition were cut to analyze the porosity. The analysis result shown in Fig. 16 indicates that the porosity becomes lower with higher laser output.

![Figure 16 Analysis result of porosity](image)

As described in section 4.1, metal powder supplied with shielding gas and carrier gas hitting the molten pool caused waves in the molten pool structure and the gas seems to enter the molten pool and remains as voids. In addition, Figs. 15 and 16 indicate that the porosity becomes lower when laser output gets higher, i.e. the solidification time becomes longer. These results indicate that as long as the solidification time is long enough, even if the gas enters the molten pool, the gas can be discharged to the outside due to buoyancy of the gas itself.
However, if this phenomenon is considered to occur due to buoyancy only, many voids are supposed to be observed on the deposited layers, but Fig. 2 does not show such a condition. This needs to be researched further.

Voids were circular instead of being awkward shapes, which means metal powder was sufficiently melted and voids were shaped in spherical shape. Therefore, bubbles acquire buoyancy in the molten metal. On the other hand, the possibility that convection occurs due to Marangoni force, entry of powder, and sprayed gas has been pointed out in the previous research (Raghavan et al., 2013), (Heigel et al., 2016). Bubbles that are bigger than a certain size are discharged outside by buoyancy of themselves, but small bubbles that are less influenced by buoyancy are evenly dispersed in the molten pool instead of being discharged due to the influence of convection (Kuriya et al., 2018). Figure 17 shows the estimated mechanism of the gas discharge.

![Mechanism of gas discharge](image)

However, the solidification time does not always coincide with the porosity. For example, when 1-layer is deposited with a laser output of 2000 W, $\Delta t$ is 0.32 second and the porosity is less than 0.1%, whereas $\Delta t$ is 0.33 second and the porosity is high as 0.3 % to 0.4 % when 21-layer are deposited with 1280 W. This phenomenon is also suggested theoretically by the influence of convection. With the laser output of 2000 W, convection inside the molten pool becomes active and gas entered in the molten pool tends to be discharged. On the other hand, with the laser output of 1280 W, convection inside the molten pool is less active and the gas tends to stay inside.

5. Conclusion

In this study, Inconel 718, which is frequently used in the aerospace and heavy electric industries, was used in DED, and the void generation was investigated through the dynamic observation by the high-speed camera, the thermal observation by the two-color temperature measurement and the evaluation of the porosity. The results in this study lead to the following conclusions.

1. As a result of deposition observation with a high-speed camera, molten pool appeared under the laser nozzle center, and metal powder supplied with shielding gas and carrier gas hitting the molten pool caused waves in the molten pool structure. Thus, the gas seems to enter the molten pool and remains as voids.

2. Higher laser output produce larger molten pool. As the result, several layers previously deposited were re-melted and solidification time becomes longer.

3. As a result of evaluating porosity, the porosity becomes lower when the laser output is higher. There would be two reasons according to the void size. In terms of large void, longer solidification time ensure sufficient time to discharge relatively large bubbles to the outside due to buoyancy of the gas itself. In small void, higher laser output generates active convection inside the molten pool so that small bubbles could be discharged easily.
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