Evaluation of correlation between baseplate temperature and deposition properties in directed energy deposition

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Abstract. Process stability in directed energy deposition is not sufficiently high to achieve high repeatability in deposition results due to residual heat. This paper summarizes the correlation between baseplate temperature and deposition result in DED in order to control heat condition around melt pool. The baseplate temperature certainly has a high correlation with porosity rate and amount of melting in deposited objects.

Introduction

Directed energy deposition (DED) is an additional processing method for forming a product by melting and solidifying material powder with laser beam. Compared with removal processing method, this processing method has advantages in high freedom of modeling, waste reduction in materials, and shortening lead time. Thus, this processing method is in high demand in various industrial fields such as the aerospace and the automobile industries.

However, DED still has problems in shape accuracy and strength of the deposited object. In particular, deformation of the deposited object due to residual heat is a fatal defect in improving the shape accuracy. The melt pool size increases according to the temperature rises; thus, temperature control is an important challenge for shape accuracy in DED.

In order to solve the overheat in melt pool, conventional researches have aimed at improving shape accuracy in DED by controlling parameters such as laser power and material powder supply. Manvatkar et al. have clarified the influence of laser power and laser feed rate on the melt pool shape, deposited shape and temperature distribution in DED by heat transfer simulation [1]. Moreover, several researchers have shown that the process control system of melt pool temperature and size exhibit a good performance in achieving uniform buildup geometry by using laser-based additive manufacturing [2,3,4]. These studies have shown that the final shape can be kept highly uniform, but the mechanical properties of deposited object have not been kept constant. Although there are many parameters that influence on deposition results, the correlation between the parameters and the deposition results still remains obscure. This paper proposes the evaluation of correlation between baseplate temperature and deposition properties in DED. As a result, the baseplate temperature certainly has a high correlation with porosity rate and amount of melting in deposited objects. In order to realize high-quality deposition processing, an important factor, baseplate temperature, is focused on in this study.
Methodology

Estimation of baseplate temperature. This study adopts a moving point heat source model [5] to estimate baseplate temperature. Irradiation point of laser is represented as a moving point heat source. Furthermore, a quasi-steady state model is introduced, which satisfies following conditions. Firstly, thermal conductivity, thermal diffusivity and specific heat are constant regardless of temperatures. Secondly, latent heat is ignored. Moreover, baseplate is modeled as a semi-infinite solid. Equation 1 shows a quasi-stationary heat conduction equation including two thermal parameters, thermal conductivity $K$ and diffusivity $k$. Therefore, the thermal conductivity and diffusivity can be calculated by solving a simultaneous equation based on the temperatures at two measurement points and the irradiation conditions. By substituting the calculated thermal conductivity and diffusivity into Eq. 1, the temperature $T$ around the heat source is estimated.

$$T - T_0 = \frac{Q}{2\pi K r} \exp\left(-\frac{v^2}{2k}\right) \exp\left(-\frac{v^2 r}{2k}\right).$$

where $T_0$ is the initial temperature, and $Q$ and $v$ are the laser power and the laser feed rate respectively. Furthermore, $r$ is the distance between measurement and heat source points, and that in the feed direction is represented as $x$.

Evaluation method of deposition properties. Figure 1 shows the specimen of deposited object. In this study, porosity rate and amount of melting are employed as indicators for deposition property evaluation.

Porosity rate. Inner void of deposited object leads to the uniformity of strength and density, which are important factors for mechanical parts. In this study, the center of deposited object is cut by using an abrasive water jet machine and its cross section is polished with a polishing machine. The cross section is observed with a digital microscope. The cross-sectional image is converted to a gray scale image in order to distinguish the void area based on luminosity as shown in Fig. 2. The porosity rate is defined as the ratio between the void area and the total cross-sectional area.

Amount of melting. A boundary line is confirmed on the cross-sectional image of bonding surface as shown in Fig. 3. Amount of melting is defined as the area between baseplate surface level and boundary line. The maximum melted depth and the melted area are used to evaluate the amount of melting.
Experimental setup

A five-axial machining center (LASERTEC 65 3D, DMG MORI CO., LTD.), built-in DED function, is used for deposition tests. Figure 4 shows the experimental apparatus. The baseplate is fixed to the jig. The metal powder is supplied toward the baseplate by carrier gas. The supplied material is melted by the laser beam and deposited on the baseplate. Inconel 625 powder (grain size of 45 to 125 μm) and S45C baseplates are used in this study. In order to estimate the temperature around the melt pool, two Ir-Rh thermocouples are inserted into the baseplate to measure the temperature at 2-mm depth from the surface. The deposition tests are conducted under various combinations of deposition parameters summarized in Table 1.

<table>
<thead>
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<th>Table 1 Deposition conditions</th>
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<tr>
<td>Laser power</td>
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<td>Carrier gas flow rate</td>
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<td>Shield gas flow rate</td>
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<td>Metal powder supply</td>
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<td>Deposition length</td>
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Results

Baseplate temperature measurement. The validity of the temperature measurement is verified by comparing the melt pool depth estimated based on the quasi-stationary heat conduction equation and the melted depth measured in the cross-sectional image of deposited objects. Figure 5 shows the example of temperature fluctuation at the measurement point of 2-mm depth. The temperature reaches to its peak value when the laser beam passes just above the measurement point. By substituting two peak temperature values measured by two thermocouples into the quasi-stationary heat conduction equation, the temperature distribution is estimated as shown in Fig. 6. The maximum melted depth and melted area are calculated by assuming the temperature of melt pool area is greater than 1500 °C, which is corresponding to melting temperature of S45C. The comparisons between the actual and the estimated values of melted depth and area are summarized in Figs. 7 and 8 respectively.
It can be confirmed that the actual melted depth and area exceeds the estimated values under almost all conditions. This difference would appear due to the assumption of the point heat source, whereas the laser beam has 3-mm diameter spot. However, the measured value and the estimated value show a linear relationship. Thus, the measured temperatures are certainly applicable to evaluate the deposition properties.

Correlation between baseplate temperature and deposition properties. Figure 9 shows the relationship between baseplate temperature and porosity rate. The correlation coefficient between the baseplate temperature and the porosity rate is highly negative as -0.8164. When the baseplate temperature is low, i.e., melt pool temperature is low, the supplied material powder does not sufficiently melt. In this case, voids easily remain existing between non-melted powders, which are contained into the deposited object.

Figures 10 and 11 show the relationship between the baseplate temperature and the amount of melting. The correlation coefficients between baseplate temperature and maximum melted depth, and melted area are 0.5608 and 0.5560 respectively, which are positive and slightly strong correlations. The higher baseplate temperature means that the amount of energy supplied from the laser beam is larger, thus the melted area gets bigger.
Summary

The correlation between baseplate temperature and deposition properties in DED is evaluated by estimating the baseplate temperature with thermocouples and quasi-stationary heat conduction equation in this study. The obtained results are summarized as follows:

1. Melted depths measured from cross-sectional images of deposited objects are compared with melted depths estimated based on the quasi-stationary heat conduction equation. The melted depth and the estimated value do not sufficiently agree with each other, but show a linear relationship with high coefficient.

2. High correlation is confirmed between the baseplate temperature and the porosity rate. The higher the baseplate temperature is, the lower the porosity rate is.

3. High correlation also exists between the baseplate temperature and the amount of melting. The higher the baseplate temperature is, the bigger the amount of melting is.
References


