Optimal laser power command generation for direct energy deposition by applying gradient descent to a thermal conductivity simulation

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Abstract
Direct energy deposition attracts attention from automobile and aerospace industries because of its applicability to complex shape production. Although the meltpool temperature has to be controlled to enhance shape accuracy, industries remain hesitant over introducing a complex process monitoring system because of high cost and necessity of frequent maintenance. In order to keep the meltpool temperature constant, this paper proposes optimal laser power command generation by creating a finite-element thermal conductivity model for a gradient descent calculation. The experimental results clearly indicate that the obtained laser power command enhances the shape accuracy of the deposited objects.

Keywords: Direct energy deposition, Additive manufacturing, Thermal conductivity, Simulation, Laser

1. Introduction

Additive manufacturing (AM) technology, although difficult to achieve in traditional manufacturing techniques, has a considerable potential for offering a new solution for cost, efficiency, and flexibility in materials and designs (Levy et al., 2003, Dongdong, 2015). AM technology involves a comprehensive integration of laser technology, material science, and mechanical engineering and is currently regarded as a revolutionary technology in the manufacturing industry (Dongdong, 2015, Lü et al., 2001). The use of high-power laser technology allows different components of a system to be manufactured from a variety of metals, thus further extending the applicability of AM technology (Gibson et al., 2010). In particular, AM is a lucrative option in aerospace and automobile industries to produce complex-shaped components with difficult-to-cut metals.

In terms of laser AM technologies for metals, powder bed fusion (PBF) and direct energy deposition (DED) are popular methods for freeform production. In order to ensure the reliability of the metal AM processes, many researchers evaluate mechanical properties of the produced parts. For example, the strength of the components manufactured in an AM production is often analyzed in terms of density, and several researchers take experimental approaches to reduce the void inside them during the production following PBF (Wits et al., 2016) and DED (Kakinuma et al., 2016, Zhong et al., 2015). The relation between the microstructure and its mechanical characteristics is also investigated for superalloys, such as Inconel 625 (Cao and Gu, 2015) and Ti-6Al-4V (Wu and Lai, 2016). Most of these studies indicate the necessity of laser power modification in the AM process to enhance the specific strength and obtain a proper metal structure.

On the other hand, shape accuracy is also an important factor in the manufacturing industry in terms of reliability. Although the production efficiency of DED is much higher than that of PBF, it is difficult to enhance shape accuracy in DED. A simulation can ensure shape accuracy by predicting the produced shape from the production conditions. Therefore, an accurate time-domain simulation is proposed for PBF (Zohdi, 2014). However, in case of DED, the
dynamic movement of metal powder and large heat supply render process analysis difficult. As a solution for laser power modification, Ding (Ding et al., 2016) developed a feedback controller that keeps the melt pool size constant by developing a monitoring system using CCD cameras. However, industries often hesitate to introduce a complicated monitoring system to their machine because of high cost and frequent maintenance. Furthermore, laser command generation is rarely a topic of discussion though the laser power should be altered according to the cooling efficiency at the machining point of the target object. Even without monitoring, the shape accuracy can be enhanced by calculating the DED laser power in advance because it can help avoid deformation due to overheating.

In this paper, we propose laser power command optimization to maintain the melt pool temperature in a DED based on a thermal conductivity simulation. A laser power command is a pre-requisite for the proposed method. Therefore, the deformation due to overheating can be avoided only with a feedforward control, i.e., without process monitoring. The calculated laser power command is installed to the DED machine and investigated by depositing three types of wall-shape parts with Inconel625 and evaluating shape accuracy.

2. Direct energy deposition

According to ASTM International (ASTM International, 2013), DED is an AM process where focused thermal energy is used to fuse materials by melting as they are being deposited. In a typical DED, the material is gradually deposited on a baseplate by heating the baseplate with a laser beam and supplying material powder to the melt pool as shown in Fig. 1. In order to prevent oxidation of the deposited object, the atmosphere around the melt pool is filled with Argon, which acts as a shield and a carrier gas. Figure 2 shows the additive/subtractive combined machine used in this study, which adopts a contentious wave laser, which has a tophat profile and a wavelength of 1020 nm (LMD2500-60, LASERLINE. Co., Ltd.). The laser spot diameter is 3 mm and the maximum laser power is 2000 W.

![Fig. 1 Schematic of direct energy deposition (DED) process. Heating a baseplate with laser and supplying powder material and protection gas, the material is continuously deposited on the baseplate.](image1)

![Fig. 2 Appearance of DED using Inconel625 powder. Heated point glows red and is in sufficiently high temperature to melt the material.](image2)

3. Laser power command optimization
3.1 Thermal conductivity simulation

Considering the cooling process in the DED, the amount of heat transferred to the air is much smaller than that transferred to the baseplate. When the heat emission is ignored for simplification, the heat distribution in DED would be predicted approximately by applying a finite-difference method with a voxel model. Generally speaking, heat diffusion in three-dimensional space is defined as

\[
\frac{\partial T}{\partial \tau} = \alpha \left( \frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2} \right) + \frac{Q}{\rho CV} \quad (1)
\]

where \( T \) [K] is the temperature of an voxel element, \( \tau \) [s] is the time, \( \alpha \) [m\(^2\)/s] is the thermal diffusivity, \( x, y, \) and \( z \) [m] are the coordinate variables, \( Q \) [J] is the external heat input, \( \rho \) [kg/m\(^3\)] is the density, \( C \) [J/(kg·K)] is the specific heat, and \( V \) [m\(^3\)] is the volume of the voxel element. Considering interaction between the adjacent elements in a voxel...
model, the second-order partial differential can be discretized as follows:

\[ \frac{\partial^2 T_n}{\partial r^2} = \frac{T_{\Delta r} - 2T_n + T_{-\Delta r}}{(\Delta r)^2}, \quad (r = x, y, z) \]  

(2)

where superscript \( n \) represents the number of time step, \( \Delta r \) [m] is the distance between the adjacent voxel elements, and \( T_{\Delta r} \) [K] and \( T_{-\Delta r} \) [K] are the temperatures of the adjacent voxel elements. Furthermore, the temporal differential is described in discrete domain as follows:

\[ \frac{\partial T}{\partial \tau} = \frac{T_{n+1} - T_n}{\Delta \tau} \]  

(3)

where \( \Delta \tau \) [s] is the step time. By substituting Eqs. (2) and (3) into Eq. (1), then, the temperature of a voxel element can be updated based on the temperatures of adjacent voxel elements and the thermal parameters of the voxel elements.

\[ T_{n+1} = T^n + \Delta \tau \left( \alpha \left( \frac{T_{\Delta x} - 2T_n + T_{-\Delta x}}{(\Delta x)^2} + \frac{T_{\Delta y} - 2T_n + T_{-\Delta y}}{(\Delta y)^2} + \frac{T_{\Delta z} - 2T_n + T_{-\Delta z}}{(\Delta z)^2} \right) + \frac{Q}{\rho C V} \right) \]  

(4)

Furthermore, the second-order partial differential is zero in surface element as follows:

\[ \frac{T_{\Delta r} - 2T_n + T_{-\Delta r}}{(\Delta r)^2} = 0, \quad (r = x, y, z) \]  

when the adjacent voxel element does not exist.  

(5)

At the bottom elements of baseplate, the temperature is fixed at 25°C in this simulation.

\[ T_{n+1} = T^n = 25 \text{ °C} \]  

when the element is placed at bottom of baseplate.  

(6)

By calculating the temperature of each voxel with Eq. (4) sequentially, time variations in temperature distribution of voxel model are analyzed. Furthermore, in the proposed model, voxels are added to the laser spot region to express the deposition process as shown in Fig. 3. The heat energy from the laser power is represented as the external heat input \( Q \) in Eq. (1), and it is applied to the surface elements in the laser spot region. The voxel size is set to \((0.4 \text{ mm})^3\) to fit the height of the deposition in one layer.

3.2 Gradient descent for laser power command generation

Gradient descent is one of the simplest optimization methods in a linear system. By setting an evaluation value \( E \) and evaluating Eq. (7) repeatedly, the vector \( \mathbf{x} \) gradually approaches a local minimum value.

\[ \mathbf{x}_{n+1} = \mathbf{x}_n - \eta \frac{\partial E(x_n)}{\partial x_n} \]  

(7)
where \( n \) is the number of steps, and \( \eta \) is the constant value. If the error between the target and the response value is set as the evaluation value \( E \), the gradient descent can obtain a vector \( \mathbf{x} \), which has the value nearest to the target.

In the thermal conductivity simulation, the maximum temperature in the melt pool is easily captured. Although the laser power can be modified in each time step during the simulation, the machine used in this study does not have a special function to modify the laser power continuously during DED. Thus, the average of maximum temperatures in a single layer deposition is calculated and compared with the target temperature, assuming that the laser power is constant in each layer. The error between the present and the target temperatures \( T_{err} \) is defined as the evaluation value and the laser power \( p \) is set as the variance. The temporal differential is conducted as follows:

\[
\frac{\partial T_{err}(p_n)}{\partial p_n} = \frac{T_{err}(p_n + \Delta p) - T_{err}(p_n)}{\Delta p}
\]

where \( \Delta p \) is the infinitesimal value for differential calculation and set to 0.01 W in this study. Furthermore, Eq. (7) can be replaced as follows:

\[
p_{n+1} = p_n - \eta \frac{\partial T_{err}(p_n)}{\partial p_n}
\]

This calculation is conducted from the bottom of deposited object layer by layer, and repeated in each layer until the error \( T_{err} \) gets less than 1°C.

4. Experiment and evaluation

4.1 Laser power command calculation

Even in a complex-shaped production in the DED, the deposition is performed on a combined track of simple linear and curved tracks. Therefore, the deposition on a simple track is an important target to evaluate the applicability of the proposed method. In this study, three kinds of tracks are chosen as targets, a linear track, a corner track, and a circular track as shown in Fig. 4. The laser nozzle makes a round trip on the linear and corner tracks in both the simulation and the experiment, although the same trajectory is continuously used on the circular track deposition.

![Deposited shapes: (a) single track deposition, (b) corner track deposition, (c) circular track deposition.](image)

At first, the simulation for the laser power command calculation is performed. The detailed parameters for the simulation are summarized in Table 1. Figure 5 shows the time variation in the temperature distribution in the deposited object under a constant laser power of 425 W, which is sufficient for the target temperature to reach 2500°C at the first layer of 30 mm single track. The high temperature area gradually spreads in higher layers. On the other hand, overheating is prevented with the laser power modified according to the proposed method as shown in Fig. 6. The relationship between the layer number and the calculated heat supply is shown in Fig. 7, which clearly indicates that the
laser power has to be smaller in the higher layers. The laser power needs to decrease by 25.5% at the 20th layer in the 30-mm single-track deposition, compared with that at the first layer. Furthermore, the decreasing rate of required heat supply becomes lower in the longer tracks as 40, 50, 60 and 70 mm. The difference in the laser powers at first layer is due to the size of baseplate. In case of a longer track, the baseplate size is also set larger, i.e., the cooling efficiency gets higher because the heat capacity of baseplate becomes larger.

Table 1  Simulation conditions.

| Parameters                          | Deposited object (Inconel625) | Baseplate (SUS304) |
|-------------------------------------|-------------------------------|--------------------|
| Density at 25 °C kg/m³              | 8440                          | 8030               |
| Thermal diffusivity at 25 °C m²/s   | 2.89×10⁻⁶                    | 3.99×10⁻⁶          |
| Specific heat at 25 °C J/(kg·K)     | 410                           | 500                |
| Feed rate of laser nozzle mm/min    | 1000                          |                    |
| Target temperature °C               | 2500                          |                    |
| Time step ms                        | 0.1                           |                    |

Fig. 5  Temperature distribution simulation result for DED using constant laser power. The temperature in deposited part gets higher at higher layer because heat conduction is small due to small cross section at high layer.

Fig. 6  Temperature distribution simulation result for DED using laser power modified with the proposed method. The modified laser power certainly suppresses overheating at the high layer.
The calculated heat supply is much smaller than the maximum laser power of 2000 W since the reflectance of nickel is > 70% when the laser wavelength is 1020 nm (Weber, 2003). In order to apply the simulation result to the DED in practice, the calculated heat supply must be multiplied by a certain constant value, considering the reflected energy.

A similar tendency is also confirmed in the corner deposition simulation, in which the calculated laser power command is between 418 W and 325 W, as shown in Fig. 8. The fluctuation in laser command is caused by the difference in approach length as show in Fig. 4(b). Furthermore, the calculated laser power command for the 20-mm diameter circular deposition also gradually decreases from 431 W to 272 W in 50-layer deposition, as shown in Fig. 9. The decreasing rate of laser power becomes lower on the 40-mm diameter track as from 425 W to 326 W.

![Generated laser power command for 20-layer deposition on the single track of 30, 40, 50, 60 and 70 mm. The laser power should be gradually decreased at high layer to keep the meltpool temperature. The decreasing rate of proper laser command is higher in shorter track.](image1)

![Generated laser power command for 20-layer deposition on the corner track. The laser power should be decreased at 22.2% at 20th layer.](image2)

![Generated laser power command for 50-layer deposition on the circular track. The decreasing rate of proper laser power is smaller than the other tracks because the deposition trajectory is longer, whereas the proper laser power gets smaller at higher layer as same as the analysis results for other tracks.](image3)
These results clearly show that the higher layers are overheated in the DED with constant laser power and that less laser power should be used in case of higher layers. Moreover, the decreasing rate of laser power at higher layers gets smaller when the deposition track becomes longer.

Although similar simulations with Gaussian beam laser are conducted in this study, these results are abbreviated in this paper because the simulations have shown no remarkable difference in the thermal distribution in the deposited part comparing the results of tophat beam laser.

4.2. Experiment

By applying the calculated laser power command to the machine after multiplying by certain value to fit the initial laser power, deposition tests are conducted using the same deposition tracks. The details of the deposition conditions are summarized in Table 2. In order to evaluate the improvement in shape accuracy with the proposed method, constant laser power deposition is also performed under the same deposition conditions except the laser power.

Figure 10 shows the appearances and cross sections of deposited objects produced on a single track of 30 mm with 20 layers. As shown in (a), the deposited object is deformed under the constant laser power of 2000 W due to overheating. On the other hand, the cross-sectional width of deposited object does not get larger at high layer when the laser power command is generated with the proposed method as shown in (b). By measuring the cross section width related to the height with a digital microscope, the variation in the width of the deposited object is summarized in Fig. 11. Considering the laser spot diameter, the target width should be 3 mm. When the laser power is modified with proposed method, the maximum error in the width is 0.37 mm in 30-mm single track as shown in (a). However, the maximum error in width is 1.28 mm under constant laser power command. In order to clarify the difference between depositions under the modified and the constant laser power, the maximum widths in the single track of each length are summarized in Fig. 12. The modified laser command certainly suppresses the increase in width due to overheat in each length of track. In particular, the proposed method can suppress the deformation even in the short track as 30 mm, whereas overheat easily occurs in high-aspect-ratio deposition.

| Table 2  Deposition conditions. |
|---------------------------------|
| Initial laser power  W | 2000 |
| Feed rate of laser nozzle  mm/min | 1000 |
| Metal powder supply  g/min | 18 |
| Carrier gas supply  l/min | 6 |
| Shield gas supply  l/min | 4 |
| Material powder size  μm | 53 – 105 |
| Material of powder | Inconel625 |
| Material of baseplate | SUS304 |

Fig. 10 Deposited objects produced on the 30-mm single track under (a) the constant laser power of 2000 W and (b) the proposed laser command modification. The cross-sectional view shows that the deformation due to overheating is certainly suppressed under the laser power command modified with the proposed method.
The improvement in shape accuracy is also observed in the corner-shape depositions as shown in Figs. 13 and 14. The error in width decreases to 0.64 mm, though it is 1.00 mm under constant laser power. Furthermore, the proposed method is evaluated in the circular track depositions as shown in Figs. 15–17. The overheat deformation is clearly observed in 20-mm diameter deposition with constant laser power of 2000 W, and suppressed with the modified laser power calculated with the proposed simulation, whereas the height of deposited object varies because the nozzle feed is stopped during the laser power changing and the extra material is deposited at the starting point of circular track. Furthermore, the extra heat energy is applied during the nozzle stop and initiates a high thermal gradient. As a result, the deposited height gradually decreases from the point of 0° to 90°. By cutting the deposited objects at the point of 270° from the starting point, width variations are measured and summarized as shown in Fig. 17. The width of higher layer is reduced from 5.18 mm to 3.82 mm in 20-mm diameter deposition. On the other
hand, no remarkable difference is observed between the deposition with constant and modified laser power in 40-mm diameter deposition. These results indicate that the meltpool temperature does not get so high to cause overheat deformation when the deposition track is long and the number of layer is small. Excepting the long track depositions, the laser power modification with the proposed method is certainly an effective approach to enhance the shape accuracy in DED. Furthermore, in our future works, the laser power modification should be performed simultaneously without stopping the nozzle feeding.

Fig. 13 Deposited objects produced on the corner track under (a) the constant laser power of 2000 W and (b) the proposed laser command generation. It is clear that the width expansion due to overheat is suppressed with the proposed laser command in the cross-sectional comparison, although no remarkable difference is confirmed in appearances.

Fig. 14 Relation between width and height of deposited object in corner track deposition. The overheat deformation at high layer is successfully suppressed with the proposed method.

Fig. 15 Deposited objects produced on the circular track of 20-mm diameter under (a) the constant laser power of 2000 W and (b) the modified laser power command generated with the proposed method. The proposed method successfully suppresses the heat deformation. The inclination in height of the deposited object in (b) occurs because the laser nozzle feed is stopped when the laser power is changed in the DED machine used in this study.
Discussion

Despite the shape accuracy being visibly enhanced while using the proposed method, the error is still present. Although the deformation is related to the melt pool temperature, other approaches, such as the variation in powder supply need to be analyzed to enhance shape accuracy. The proposed method would be useful to improve the metal structure rather than the shape accuracy in terms of thermal behavior. One of the challenging factors in DED, the shape error between the inner and outer sides needs to be resolved as well, particularly in corner track depositions. Figure 18 shows the summary of the measurement results of the distance from the surface to the center line. The deformation from overheating increases in size on the inner side than on the outer side. This phenomenon can be predicted from the simulation result, as shown in Fig. 19. This difference in behavior is difficult to resolve with modification in the laser power and therefore, other approaches, such as a special track design should be used. These challenges still remain in the enhancement of the shape accuracy in DED.

Fig. 16  Deposited objects produced on the circular track of 40-mm diameter under (a) the constant laser power of 2000 W and (b) the modified laser power command generated with the proposed method. No remarkable difference appears in the width of deposited objects because the deposition trajectory is so long that overheat does not occur.

Fig. 17  Relation between width and height of deposited object in circular track deposition of (a) 20-mm diameter and (b) 40-mm diameter under the constant and the modified laser power command. The overheat deformation only occurs in 20-mm diameter track and is successfully suppressed with the proposed method.

4.3. Discussion
5. Conclusion

This paper proposes laser command generation to keep the moltpool temperature constant in DED based on the thermal conductivity simulation and the gradient descent method. The experimental results clearly show that the proposed laser command does not overheat and decreases the shape error in the deposited object of single, cornered and circular tracks without a monitoring system. In particular, the error in the width of deposited object drastically decreases from 1.28 mm to 0.37 mm in 30-mm single track, and from 2.18 mm to 0.82 mm in 20-mm diameter deposition. These results indicate the proposed method would be necessary to be applied specially in short track depositions.

In a future study, shape accuracy will be improved further by analyzing and modifying the other conditions, such as the metal powder supply and the deposition track design, and constructing the laser power modifying system independent from the nozzle feeding control.

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