Identification of Dynamic Process Response in DED-Type Additive Manufacturing Process and Its Application to Process Optimization

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Abstract: For aiming at successful operation of directed energy deposition (DED) type additive manufacturing (AM) system, three different kinds of process elements, machine motion, powder supply and laser application, needs to be synchronously controlled for accurate shape creation of the work piece. In order to synchronize these elements, in this study, measurement method of these response delay time has been proposed. According to the method, using the specific DED type AM system, the response delay time has been identified as that of laser application is 0.72 ± 0.2 second and the powder supply control has about 15 seconds response time delay while the evaluated response delay time of nozzle motion was negligible compared to that of other two elements. Using identified response characteristics, dead time compensation control has been adopted to absorb the response delay time of laser and powder application processes. Laser application commands were indicated prior to reaching targeted positions and a pseudo motion command was inserted to absorb the response delay time of powder supply before starting the subsequent actual deposition with the correct powder supplied amount. Performing experimental studies, target deposition shapes have been achieved without unintended deposition and effectiveness of the proposed optimization method has been confirmed.

Key words: additive manufacturing, directed energy deposition, process optimization, dynamic process response

1. Introduction

Additive Manufacturing (AM) has been evolved over the last three decades as one of the promising future-oriented manufacturing technologies. Early AM applications in the 1980s focused on polymer-based materials, while the 1990s were a period of growth for the metal-based AM processes 1). The technology of layer-by-layer construction used in a selective laser melting (SLM) has evolved with technologies like a directed energy deposition (DED) type aiming for expanding its ability not only to build up fully dense parts but also to repair worn out high value components or apply coating to existing parts 2)-4). Therefore, the application in such areas has drawn significant interests from energy, aerospace and medical industries to this technology 5).

For successful operations of DED-type AM system, it is necessary to adjust the deposition amount at exact positions along the tool path. In addition, the deposition amount is influenced by laser power, material volume supplied from deposition tool nozzle and laser applied time 5). Therefore, process elements such as laser application, powdered material supply and nozzle motion which is the movement of the tip of the nozzle with respect to the material to be deposited in the three-dimensional space need to be controlled synchronously along the deposition path for fabrication of a targeted part geometry. For DED-type AM systems, while it is ideal if all process elements are able to be controlled using one Numerical Control (NC) system of the base machine, AM systems need to have additional control modules for the elements if they are not able to be controlled directly by the NC system. In general, the commands to operate the elements are written in a NC program with the nozzle position set and the NC program is read in the NC system being followed by transmission of the commands from the NC system to the control module of each element. These successive processes result in the response time delay of the information processing and transmitting, and the response time delay necessary for having the elements start operating mechanically after receiving the command. The problem is that laser application and powdered material supply response in significant slow speed compared to nozzle motion. Therefore, it is highly important to measure the response time delay of the elements and compensate the time delay. On the other hand, the responsiveness of such DED-type AM system where multiple elements operate variably is not yet widely studied.

In this paper, in order to control the process elements of DED-type AM system precisely in terms of time according to the target geometry and fabricate accurate shape of the work piece, identification method of response characteristics has been proposed and the response time of laser application powder supply and nozzle motion has experimentally been measured. Using identified response characteristics, dead time compensation control method that issues commands in advance to the timing when the commands are required in a feedforward manner has been also proposed and its effectiveness has been confirmed empirically.
2. Principle and dynamic behavior of the DED process

2.1 Principle of DED

In the DED process, metal powder is supplied at the same time a work piece is irradiated with a laser beam. Laser energy melts and creates a melt pool on the substrate surface. Simultaneously, supplied powder is injected into the melt pool where it fuses with the work piece. By repeating this process layer by layer, a product is created. Figure 1 illustrates this DED principle in the case of using a coaxial type nozzle. There is another type nozzle feeding powder only from one side, which configuration restricts the nozzle motion direction. In this study, coaxial type nozzle has been chosen taking its advantage employed in the formation of metallic parts from 3D designs. To carry metal powder and supply shield gas which protects the laser optical lenses from powder, Argon gas was used. The gas also plays a role in purging the atmosphere locally from the melt pool area preventing oxidization.

From the viewpoint of principles stated above, melt pool formation with the sufficient temperature, stable size and forming speed is essential for successful deposition. These characteristics are controlled by the amount of applied laser power and the laser nozzle feed rate, and therefore these process parameters need to be controlled. An example which shows this important relationship is a case that the laser nozzle feed rate decreases when the motion direction changes at a corner portion of a part. In such case, the laser power must be modulated to keep the power density constant. In addition, the deposition amount can be influenced directly by the amount of supplied powder. Due to these correlations, it requires to control synchronously and dynamically these parameters for fabrication of a targeted part geometry.

2.2 Dynamic behavior of DED

For achieving successful DED-type additive manufacturing process, it is important to identify process response to changes in parameters. Figure 2 illustrates the configuration of DED-type AM system used in this study. The main machine is designed to use the base structure of a traditional five-axis milling machine. The laser head including the nozzle is mounted on the spindle head of the machine which position can be controlled by X, Y and Z feed axis. A deposited work is generated on the side of the machine table which posture can be controlled by A and C rotation axis. The laser beam is delivered by a laser light fiber from the laser unit to the laser head and exits from the nozzle through optics inside of the laser head, then a work piece set on the table is irradiated by the laser beam. Laser source type is fiber coupled diode laser which power can be changed from 0 to 2,000W. Metal powder is fed from a powder feeder beside the machine to the laser head by using carrier gas. Shield gas supplied to the laser head is also provided by the same gas source as carrier gas and the amount of gas having the two different purposes can be regulated independently.

Figure 3 shows the control block diagram of the system. The process parameters include the powder mass flow rate (\(=Q_{\text{pow}}\) [g/min]), the laser power (\(=P\) [W]) and the nozzle feed rate (\(=F\) [mm/min]) can be defined as the process variables in a NC program. Commands to change processing variables during deposition are defined using coordinate positions. For example, in the NC program shown in Fig. 3, it is intended to decrease the laser power from 2,000 W to 1,400 W when the nozzle starts to move from Y-40 to Y-20. When executing a NC program, these variables become in effect with response time delay. Such delay
indicated as $\Delta r$ in Fig. 3 consists of processing time of the controllers and response time based on the mechanical motion of each unit. For example, in the case of powder supply, commands for changing the variable load within $\Delta r_{NC}$ in NC of the based machine tool and are transmitted to the powder feeder controller taking $\Delta r_{PLC-PCC}$. Then, within $\Delta r_{PCL-PFU}$ a signal is sent from the controller to the powder feeder unit and it takes $\Delta r_{OEU}$ from the moment when a disk starts rotating upon receiving a signal to the moment when powder exits the tip of the nozzle. Regarding the response delay time of the laser power, in fact, it should include not only $\Delta r_{NC}$, $\Delta r_{PLC-LPC}$, $\Delta r_{PCL-LU}$ and $\Delta r_{P}$ described in Fig. 3, but also melt time of a substrate or pre-deposited portion from the moment when the substrate is irradiated with the laser beam, and these material properties strictly need to be taken into account for estimating the melt time.

However, in this study, it has been assumed a melt pool is generated immediately after application of the laser beam and reaction time is negligible compared to above response delay time.

In the study, response time difference between these process variables has been evaluated as described in the following chapter by carrying out a series of experiments using the stainless steel 316L powder (particle size distribution ranges: 45–106μm) and D2 tool steel as a substrate.

3. Identification of response time delay

3.1 Laser power

The response delay time of laser power control was experimentally measured and identified. In the experiments, linear deposition with step increments of the laser power was conducted. When the NC command is executed in the CNC controller, the laser power command value is sent to the laser power controller through PLC and the controller transmit a command to the laser unit, then the laser power is adjusted to the target value. Such dynamically adjusted laser power was recorded with the position of the moving nozzle in the laser power controller and the measured results were obtained as a history of the laser power with respect to the position of the nozzle. It should be noted that this recorded value is collected from the laser power controller and not from the laser unit. Therefore, the laser power actually changes a certain time, which is indicated by $\Delta r_{t}$ in Fig.3, after the recorded timing. This response time is the specified value of 50 μ second for the laser unit used in this study and leads an assumption that this time can be negligible. In addition, while this recorded value includes the response time delay to the nozzle position, this delay is the same delay as the delay to read a NC program and it has been assumed that it is too small and can be negligible compared to the response timed delay of the laser power change. Figure 4 shows an example of such experimental results obtained.

According to the figure, even though the laser power was commanded to decrease from 1,300 W to 1,200 W at the position of -40 mm, it was recorded that the laser power started reducing at the position of -28 mm. So, the laser power has approximately 12 mm distance delay when the nozzle feed is moving at 1,000 mm/min. This means that the laser power control change has about 0.72 second response time delay.

It should be noted that response time delay of the laser power identified as above is happened when the laser power changes from a certain value to another value while it should be also defined for the case that laser application is started or stopped. As a matter of fact, responsiveness differs in both cases of starting/stopping and increasing/decreasing, since the M command is used when the laser is turned on and off while H command is used for increasing / decreasing the laser power. At once the M command is executed, nozzle motion stalls for a moment until the laser is surely turned on and off. Due to this processing rule, distance delay of starting and stopping of laser application is approximated by zero. Therefore, in this study, by paying attention to the responsiveness in case of increasing / decreasing the laser power, responsiveness was identified. And it was defined by the time the laser power started to change after the change timing commanded by a NC program as described above. It should be also noted that to minimize error in this approximation from the acceleration of the nozzle feed axis, an approach distance was used to allow the machine to have sufficient time to get to this speed. Using values described in the section 2.2, this identified response delay time of the laser power can be expressed by $\Delta r_{f}$ which is the summation of $\Delta r_{NC}$, $\Delta r_{PLC-LPC}$ and $\Delta r_{PCL-LU}$. In experiments such measurements were repeatedly performed under the different nozzle motion speeds of 500 and 1,000 mm/min. As the result, Table 1 has been obtained and it has been concluded that the typical response time delay of the laser power was 0.72 ± 0.2 second.

3.2 Discussion of laser power response time delay

As described in section 3.1, in this study, the response delay time of the laser power was defined as the time between the times when the laser power is commanded to change by a NC program and the laser power started to change. The reason for this is that this definition was preferable to create a NC program from the target deposition shape. In this definition, while the nozzle is
moving, the deposition process is still being carried out with the “old” laser power at the moment (or position) when the power change is commanded, and at the next moment deposition process is carried out with the “new” laser power. For example, when changing the laser power from 1700 W to 0 W and stopping the deposition process by 0 W instead of turning off the laser as performed in section 4.1, in order to complete the shape of the corner, at the moment the nozzle moves just to the corner, the laser power should remain 1700 W and the deposition process is carried out with that laser power. To do such deposition, it only needs to give a command to change the laser power at the moment the nozzle reaches the corner and creating such a NC program is relatively easy. However, this idea only applies when changing the laser power from a value greater than zero to zero. It can be considered that the appropriate definition of the response delay time of laser power differs depending on how to change the laser power. Furthermore, the definition could have a relationship with how to create a NC program to achieve the target geometry. These points are future work of this study.

In addition to the definition of the response delay time, the variation of ± 0.2 second measured in section 3.1 also needs to be discussed. The variation did not depend on the change amount of the laser power nor the change direction (increasing / decreasing) and occurred even under the same condition. The following things can be considered as factors causing this variation. First, data collection of the position of the moving nozzle from the NC system works with 10Hz (0.1 sec) or less frequency. Second, data of the laser power and the position of the nozzle is recorded to the data file with 10Hz or less frequency. Furthermore, those processes are not perfectly synchronized. Even though the laser power is changed in the PLC, if the moment of the change is in the middle of or just after collection cycle and the laser controller cannot catch the value, the value is recognized in next collection timing. The same thing can happen when the data is recorded from the laser controller to the data file. For eliminating the variation of measured response delay time of the laser power and carrying out accurate response time measurement, it needs to improve above three things in the future.

3.3 Powder mass flow rate

In the study, the actual response time of powder supply was experimentally measured by video camera used monitoring the dynamic change of the powder weight when the only powder was being fed into the bottle, which was placed on the digital scale. Figure 5 shows an appearance of the experiment. Figure 6 shows the result of such experiment of dynamic powder weight measurement when the NC commands of changing the powder mass flow rate in a step wise manner were executed through the CNC controller. Actual powder mass flow rate, \( Q_{m(t)} \), in the figure was calculated by Eq. (1).

\[
Q_{m(t)} = (M(t+\Delta t) - M(t))/\Delta t
\]

In the above equation, \( M(t) \) is the monitored accumulated powder weight. In this experiment, \( M(t) \) was collected every one second and \( \Delta t \) was set to 10 seconds. Difference between the target timing and the timing when the calculated powder mass flow rate has achieved the targeted powder mass flow rate first time is defined as the response time delay. This definition was modified in the case of starting powder supply to be the difference between the target timing and the timing when the calculated powder mass flow rate has returned to the targeted value again after overshoot.

Table 2 shows the delay measured in such manner from Fig.6. As shown in this table, it was identified that the powder mass flow rate control had about 15 seconds response time delay for the actual powder mass flow rate to reach the targeted value after NC command is given to the CNC controller. According to discussion in the section 2.2, this identified response delay time of powder supply can be also represented by \( \Delta t'_{om} \), which is the summation of \( \Delta t_{NC} \), \( \Delta t_{PLC-PFC} \), \( \Delta t_{PFC-PFU} \) and \( \Delta t_{om} \). It should be noted that the results would be more accurate if measurements could be digitally recorded directly from the scale.

![Fig. 5 Appearance of powder mass flow rate measurement.](image)

![Fig. 6 Powder mass flow rate change against NC commands.](image)

<table>
<thead>
<tr>
<th>Range of change [g/min]</th>
<th>Response time delay [sec]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 - 11.1</td>
<td>15</td>
</tr>
<tr>
<td>11.1 - 14.7</td>
<td>15</td>
</tr>
<tr>
<td>14.7 - 18.4</td>
<td>15</td>
</tr>
<tr>
<td>18.4 - 21.9</td>
<td>16</td>
</tr>
<tr>
<td>Ave.</td>
<td>15</td>
</tr>
</tbody>
</table>
3.4 Summary of response time delay

A similar method to the one described in the section 3.1 was used to attempt to determine the response time delay of the nozzle feed rate command. Instead of using measurements recorded by the laser power controller, measurements of the deposition height which correlates directly to changes in the nozzle feed rate were conducted to detect the position of the nozzle feed rate change relative to the programmed position. However, after viewing the measurement results of the deposition geometry, it was found that the nozzle feed rate change occurred too rapidly to use this type of measurement to approximate the response delay time. Therefore, the response delay time of the nozzle feed rate was estimated by using a built-in NC controller recording function of axes velocity. As a result, it was monitored that it took 0.04 second to accelerate from 0 to 1,000 mm/min under the sampling frequency of 0.004 second. This value was evaluated as \( \Delta T_F \). An overview of the response time for each of the parameters is shown in Table 3. From this table, although the evaluated response delay time of the nozzle feed rate should depend on the amount of change, it is negligible compared to that of other parameters when designing additive operations. Furthermore, other parameters include the powder supply stirrer speed and the carrier gas flow rate. Dynamic response values were not studied for these parameters because they typically remain constant during additive operations. It should be noted that although the carrier gas flow rate can be thought to affect the response time delay of powder supply, it should be firstly fixed in terms of optimizing oxidation.

4. Dead time compensation control and its verification

4.1 Laser application

Using the identified response delay time in the previous chapter, dead time compensation control tests of laser application were performed as below. As shown in Fig. 7, over deposition and no deposition occurred during the deposition of rectangular corner shape when the position of the laser power change was set to be exactly at the corner in the CNC program. Here, the nozzle was moved along Path I to V, the laser power change positions commanded by the CNC program are indicated by A and B. The reason why the nozzle feed path includes blue paths (Path II to IV) is to prevent deposition from being excessively at the corner where the feed motion has to stop to change directions in the case of the consecutive path consists of only red paths (Path I and V). Due to the response time delay, the substrate was continued to be irradiated with the laser beam and over deposition occurred even after the laser power change command from 1,700 W to 0 W was executed at Position A. In addition, deposition didn’t restart until the laser nozzle passed through Position B where deposition was supposed to be started. It should be noted that at the start and end points of the rectangular shape this unintended deposition did not occur since the laser itself was turned on and off by executing the M command explained in section 3.1. In order to avoid such unintended deposition, the laser power change positions were modified to be prior to reaching the corner as shown in Fig. 8. Length of \( d \) indicated in the figure is the distance which the laser nozzle feeds within the response delay time and is calculated by Eq. (2).

\[
d = F \cdot \Delta T_F
\]  

In this experiment, the nozzle feed rate, \( F \), of 1,000 mm/min was used and the laser power change positions were set to be 12 mm before and after the corner in the CNC program respectively as Position A' and B' shown in Fig. 8. It should be noted that Eq. (2) only works for straight path segments that have no changes in acceleration. Moreover, additional linear approach motion was added to Path IV to get up to the velocity before the laser power change command was called and the nozzle was traveling the distance \( d \). As shown in the figure, rectangular corner shape was obtained without unintended deposition by this compensation and thin wall shape displayed in Fig. 9 was also achieved by repeating the modified CNC program 20 times with increment of Z position by the amount of the layer height for every layer at the same work coordinate. It should be noted that from above compensation was performed successfully even though it was carried out considering only the response delay time of 0.72 second, not taking the variation of ±0.2 second into consideration. From the experimental results, it can be said that the variation of ±0.2 second does not strongly affect the deposition result. On the other hand, as far as it is measured from the data collected from the laser controller, the response delay time of laser power change has a variation of ±0.2 second. Since the reason for this is still unclear, it needs to pursue further in the future.

### Table 3 Response delay time of process elements.

<table>
<thead>
<tr>
<th>Process element</th>
<th>Symbol</th>
<th>Value [sec]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Laser application</td>
<td>( \Delta T_F )</td>
<td>0.72±0.2</td>
</tr>
<tr>
<td>Powder supply</td>
<td>( \Delta T_m )</td>
<td>15.0</td>
</tr>
<tr>
<td>Nozzle motion</td>
<td>( \Delta T_w )</td>
<td>0.04</td>
</tr>
</tbody>
</table>

(a) Nozzle path and laser power change commanded positions

(b) Deposition result

Fig. 7 Deposition of rectangular corner shape without application of dead time compensation control of laser.
The nozzle feed rate, \( F \), was set to 1,000 mm/min and \( A_p \) was calculated to 250 mm using the value of \( \Delta r_{qm} \) determined in the chapter 3. If a pseudo motion is linear or circular, no acceleration occur during the motion and \( A_p \) is calculated as the minimum required distance to achieve the targeted powder mass flow rate. On the other hand, in the case of the pseudo motion like Fig. 11, the motion is accelerated and decelerated around the corners, thus it takes more time to move this distance. This means that it allows the machine sufficient time to reach the target value. As shown in Fig. 11, the deposition height was adjusted at the expected position by this compensation.

Figure 12 shows cross-sectional shape of stepped line deposition shown in Fig. 10 and Fig. 11, which was measured using coordinate measuring machine (CMM). As shown from this figure, by compensating for the response delay of powder supply amount change, deposition height was changed at the target position of 20 mm (red line). By contrast, with respect to the height of the stepped line deposition obtained without compensation (blue line), the flat portion was measured between the position of the target of 20 mm and the position of 60 mm where the deposition height starts to increase. This portion indicates that it takes a certain amount of time for the powder feeder to start moving and for the powder to start being injected from the tip of the nozzle to change the supplied amount even if the change is commanded. In addition, the inclined portion seen after 60 mm shows that the powder supply amount has gradually

\[
d_p = F \cdot \Delta r_{qm}
\]

Fig. 10 Stepped line deposition without application of dead time compensation control of powder supply.

Fig. 11 Stepped line deposition with application of dead time compensation control of powder supply.
changed without immediately reaching the target value. This compensation of the response delay time can be proposed as an effective method to increase or decrease the deposition amount sharply according to the part geometry.

The objective has been achieved by the proposed method to compensate for the response delay of laser power and powder supply amount change in terms of the point that the obvious difference from the target shape has been eliminated and accurate shapes have been created. At the same time, there is still the remaining challenge that the response delay time has to be eliminated to create the accurate shape as in a short time and with high productivity as possible.

5. Conclusion

Aiming at successful operation of DED-type AM system by synchronization of the process elements, the response time was identified and dead time compensation control using the identified responsiveness has been adopted.

1. The typical response time delay of the laser power was identified as 0.72 ± 0.2 second based on the comparison between commanded and recorded positions of the laser power change.

2. Performing dynamic supplied powder weight measurement and calculation of its time-based change, it was identified that the powder mass flow rate control had about 15 seconds response time delay.

3. Executing NC programs which indicate laser application commands prior to reaching targeted positions, rectangular corner shape and its multiple layered thin wall were deposited without unintended deposition.

4. Including pseudo motion commands to absorb the response delay time of powder supply, the deposition height was adjusted at the targeted position.

References


