Technical Paper:

In-Process Height Displacement Measurement Using Crossed Line Beams for Process Control of Laser Wire Deposition

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We propose the use of the line section method with crossed line beams for the process control of laser wire deposition. This method could be used to measure the height displacement in front of a laser spot when the processing direction changes. In laser processing, especially laser deposition of metal additive manufacturing, the laser process control technique that controls the processing parameters based on the measured height displacement in front of a laser processing spot is indispensable for high-accuracy processing. However, it was impossible to measure the height displacement in front of a processing laser spot in a processing route in which the processing direction changes as the measurement direction of the conventional light-section method comprising the use of a straight-line beam is restricted although the configuration is simple. In this paper, we present an in-process height displacement measurement system of the light-section method using two crossed line beams. This method could be used to measure the height displacement in a ±90° direction by projecting two crossed line beams from the side of a laser processing head with a simple configuration comprising the addition of one line laser to the conventional light-section method. The height displacement can be calculated from the projected position shift of the line beams irrespective of the measurement direction by changing the longitudinal position on the crossed line beams according to the measurement direction. In addition, the configuration of our proposed system is compact because the imaging system is integrated into the processing head. We could measure the height displacement at 2.8–4 mm in front of a laser processing spot according to the measurement direction by reducing the influence of intense thermal radiation. Moreover, we experimentally evaluated the height displacement measurement accuracy for various measurement directions. Finally, we evaluated continuous deposition in an "L" shape wherein the deposition direction was changed while using a laser wire direct energy deposition machine for the laser process control based on the in-process height displacement measurement result. We achieved highly accurate continuous deposition at the position wherein the processing direction changes despite the acceleration and deceleration of the stage by laser process control.

Keywords: process monitoring, height measurement, light-section method, process control, additive manufacturing

1. Introduction

In various machine processing methods, the process monitoring technique for the process control is essential for high-accuracy processing [1]. In particular, in laser processing [2], many in-process on-machine non-contact measurements have been researched [3]. Meanwhile, metal additive manufacturing (AM) [4–8], which can be used to fabricate complex shaped parts quickly and inexpensively, has recently been researched in many fields, such as the biomedical [9], aerospace [10, 11], and machine tools fields [12]. The market for AM production and associated services is expected to grow to $35.6 billion by 2024 according to Wohlers Associates [13]. AM technology for commercial products has also been developed. Mitsubishi Electric Ltd. presented the metal AM machine used for the laser wire direct energy deposition method (laser wire DED) as a reference exhibit in JIMTOF 2018 (The 29th Japan International Machine Tool Fair) [14, 15]. Laser wire DED can be used to fabricate complex shapes quickly via five-axis deposition. However, laser deposition, in which an additional metal material is melted using a processing laser, is a complicated process. Hence, laser process control is indispensable because it is difficult to realize highly accurate processing owing to the influence of changes in the laser processing environment, even if the processing parameters have been optimized in advance. Accordingly, a process monitoring technique has been researched aggressively for realizing high-quality fabrication with metal AM [16], for example, melt pool imaging using a camera [17, 18],

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thermal measurement of a melt pool [19, 20], and height measurement of a weld bead [17, 18, 21, 22]. Controlling the weld-bead height within an optimal range for focusing the processing laser by measuring the weld-bead height displacement is necessary for high-quality deposition [18, 21, 23].

We proposed a compact in-process height displacement measurement system that makes use of the light-section method [24] for laser wire DED [25, 26]. This height displacement measurement system that uses the light-section method compactly consists of an integrated imaging system in a processing head sharing an objective lens for laser processing and an illuminating system that projects a straight-line beam obliquely to the imaging axis. Additional processing time was not required owing to the lack of a separate measurement process because the height displacement in front of the laser processing spot could be measured without contact during the laser processing. Furthermore, we could measure the bead height in front of the laser processing spot during the laser processing with the same ± 50 μm accuracy as without laser processing by decreasing the influence of the intense thermal radiation generated at the laser processing spot. This result was less than the necessary target accuracy of ± 150 mm of the bead height displacement for continuous deposition without the formation of droplets and stubbing. In addition, we achieved high-quality continuous deposition of a cylinder using C-axis over 50 mm height irrespective of the Z pitch and cylinder diameter by optimally controlling the wire-feeding speed based on the in-process height displacement measurement result. Thus, the feedforward control of the process parameters or the height of a processing head based on the workpiece height displacement in front of a laser processing spot can be applied not only in metal AM, but also in various other processing fields such as laser cutting and laser welding.

The configuration of the height displacement measurement system of the conventional light-section method comprising the use of a straight-line beam is considerably simple. However, it may not be possible to measure the height displacement in front of a processing laser spot using this method because of the measurement direction restriction when the processing direction changes in the case of a complicated processing route. The height displacement in front of a laser processing spot could not be measured when the processing direction was parallel to the longitudinal direction of the line beam, although the height displacement could be measured when the processing direction was perpendicular to the longitudinal direction of the line beam. In the case of the deposition process, the height displacement in the processing route is measured by stopping the deposition process after every single-layer deposition, and it is possible to fabricate complex shapes by laser process control during the deposition of the next layer. However, a reduction in the entire process time is required because of the measurement time that was additional to the processing time when the height displacement was measured in advance. Although the optical coherence tomography method used in laser welding can be used to scan the measurement position arbitrarily using a Galvano scanner [27], this method is unsuitable for on-machine measurement because of its large, complex optical system. Hence, an in-process on-machine measurement system with a simple configuration that can measure the height displacement in front of a laser processing spot without increasing the measurement time when the measurement direction changes is required for highly accurate processing.

Therefore, we propose a line section method comprising the use of two crossed line beams such that the height displacement in front of a laser processing spot during laser processing can be measured when the processing direction changes. In this paper, we present the proposed height displacement measurement methodology using crossed line beams and the configuration of our on-machine in-process height displacement measurement system. Furthermore, we demonstrate the effectiveness of our proposed method by experimentally evaluating the height displacement accuracy in the measurement direction. Finally, we clarify the improvement in the deposition accuracy via laser process control when the deposition processing of a complicated processing route changes the processing direction using a laser wire DED machine.

2. Method

First, the height displacement measurement method of the line section method comprising the use of crossed line beams is explained. Next, the principle of laser process control based on the height displacement measurement result of the line section method using crossed line beams is presented.

2.1. Height Displacement Measurement

To illustrate our proposed height displacement measurement methodology using two crossed line beams, we present the configuration of the projected crossed line beams in **Fig. 1**. In this system, two line lasers are attached at the side ($+X$ direction) of the processing head, as shown in **Fig. 1(a)**, and these lasers project the crossed line beams onto a workpiece. In this study, the $+X$ direction in the X-Y plane is defined as the 0° direction, as shown in **Fig. 1(b)**. This illustrates that when the deposition processing direction changes from the $+X$ direction to the $+Y$ direction. This system can project the line beam in front of a processing laser spot in $\pm 90°$ directions from $-90°$ in the $-Y$ direction to 0° and $+90°$ in the $+Y$ direction. Therefore, the height displacement of a weld bead in front of the processing position can be measured when the processing direction is within $\pm 90°$ directions from $-90°$ to 0° and to $+90°$ because the height displacement in the $-X$ direction cannot be measured owing to the fed metal wire. In contrast, in the conventional line section method, the bead height displacement in front of the processing position can be measured only to approximately the 0° direction; however, it depends on the line beam length,

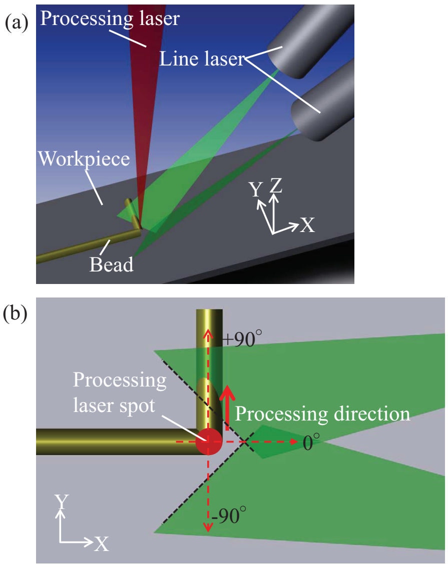

Fig. 1. Configuration of crossed line beams: (a) perspective illustration of crossed line beams and (b) illustration of line beams on a weld bead in the X-Y plane. The $+X$ and $\pm Y$ directions in the X-Y plane are respectively defined as the 0° and ±90° directions.

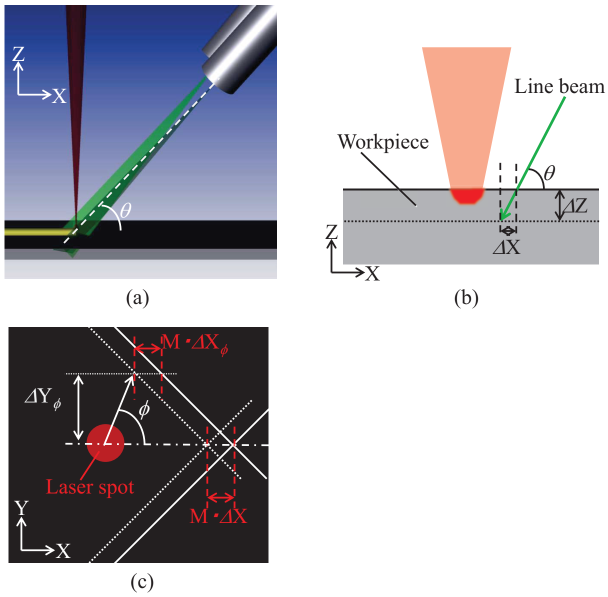

Fig. 2. Measured height displacement by projection-position shift of line beam: (a) illustration of crossed line beams in the X-Z plane, (b) illustration of line beam and a workpiece, and (c) image of crossed line beams.

because a straight-line beam is projected perpendicularly to the $+X$ direction. As a result, a height displacement measurement method comprising the use of crossed line beams can be measured in the $\pm 90°$ direction by simply adding a one-line laser to the conventional light-section method.

Figure 2 presents the relationship between the measurement height displacement and the projected position shift of the crossed line beams. The crossed line beams are projected onto a workpiece with a projection angle θ in the X-Z plane, as shown in **Fig. 2(a)**. **Fig. 2(b)** shows that the height displacement of the workpiece is ΔZ higher than the basic height. The dotted line in **Fig. 2(b)** represents the basic height, which is the focus position of the processing laser and the height displacement measurement system. The projected position shift ΔX of the line beam owing to displacement ΔZ is presented in Eq. (1) using the projection angle θ based on the triangulation principle:

$$\Delta Z = \Delta X \cdot \tan\theta. \qquad (1)$$

In this proposed method, the projected position of the crossed line beams is ΔX shifted along the X direction irrespective of the measurement direction when the measurement height changed because the crossed line beams were projected by the projection angle θ from the $+X$ direction. A schematic of the crossed line beams on a camera image when the crossed line beams are projected onto a flat workpiece is presented in **Fig. 2(c)**, where the dotted line represents the position of the crossed line beams at the basic height. The position of the crossed line beams shifts at the solid line position because the position of the crossed line beams on an image is shifted by $M \cdot \Delta X$ in the X direction when the height displacement of a flat workpiece from the measurement system is changed by displacement ΔZ, where M is the transverse magnification of the imaging system. When the processing direction is in the $+X$ direction (0° direction), the height displacement is measured by the shift in the line beam at the center of the Y direction in an image, which is identical to the conventional method. In this case, the measurement position at the center of the Y direction is the intersection of the two line beams. Meanwhile, when the processing is in the ϕ-degree direction, the height displacement is measured by the line beam's shift at the ΔY_ϕ position from the center of the Y direction in an image. Accordingly, this system can be used to measure the height displacement in the $\pm 90°$ directions, that is, from $-90°$ to $+90°$ by estimating the X-direction shift of the line beams in the Y-direction position ΔY_ϕ corresponding to the measurement direction. The Y-direction position ΔY_ϕ corresponding to the measurement direction can be estimated via communication between the height displacement measurement system and a numerical control (NC) machine. The NC machine calculates the processing direction from the estimated processing route, and the measurement direction can be calculated using this estimated processing direction. The height displacement ΔH is equivalent to the shift in the line beam that is equal to 1 pixel of a camera, which indicates the sensitivity of the height displacement measurement; this is shown in Eq. (2) by the shift $M \cdot \Delta X$ in the line beam on a camera image, wherein the camera's pixel size is P:

$$\Delta H = \frac{P}{M} \tan\theta. \qquad (2)$$

In this system, the position of the line beam in the

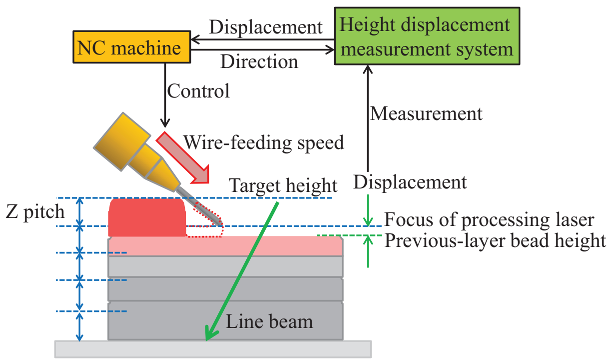

Fig. 3. Configuration of wire-feeding speed control system using in-process height displacement measurement system using crossed line beams.

camera image is estimated using the centroid of the projected line beam. We estimated the centroid position of the crossed line beams in the Y-direction position on a flat workpiece at a basic height in advance. The height displacement was calculated using Eq. (2) using the difference between the measured centroid position and the centroid position of the basic height. The height displacement calculated from the difference from the basic height is the displacement from the focus position of the processing laser, and is the target value of deposition height. Hence, the height displacement calculation process in the line section method comprising the use of crossed line beams is simple because the height displacement is calculated irrespective of the measurement direction by estimating the shift of the line beam along the X direction at the Y-direction position corresponding to the processing direction. Although the configuration projecting the line beams from various directions is assumed to measure the height displacement irrespective of the measurement direction, the height displacement calculation is complicated owing to the change in the centroid calculation direction of the line beams in an image by the line beam projection directions. Consequently, our proposed line section method comprising the use of crossed line beams can be used to measure the height displacement from almost the 0° direction of the conventional method to the ±90° direction in the X-Y plane, although the configuration is compact and the height displacement calculation process is simple. Furthermore, this system can be used to measure the 360° direction by projecting the crossed line beams from the $-X$ direction.

2.2. Laser Process Control

Figure 3 presents the optimal control system of the deposition parameters based on the in-process height displacement measurement result of the line section method using crossed line beams. In laser wire DED, the deposition height of each layer is unequal owing to thermal storage, although the Z-stage pitch was conventionally constant when depositing each layer in the multi-layer deposition. Therefore, we controlled the wire-feeding speed

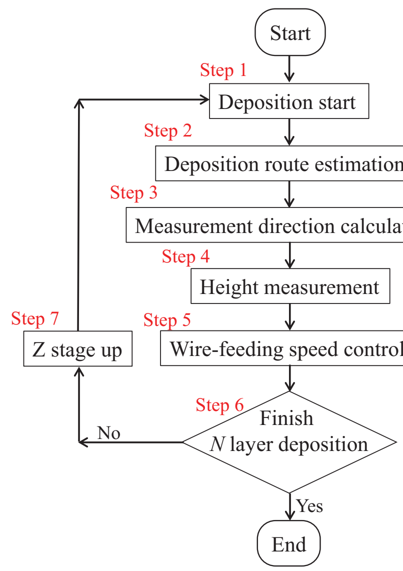

Fig. 4. Flowchart of continuous deposition process with wire-feeding speed control system using in-process height displacement measurement system.

using an NC machine based on the measured bead height displacement from the target value of the previous layer such that the deposition height reached the target height when the next layer was deposited [18]. Therefore, the bead height during deposition can constantly be equal to the target height, which is the focus position of the processing laser. The flowchart of the continuous deposition process by the wire-feeding speed control system and the in-process height displacement measurement system using crossed line beams is presented in **Fig. 4**. A laser wire DED starts the deposition by starting the processing laser and wire-feeding at step 1. The crossed line beams also scan along with the processing spot, which is scanned on the processing route. The NC machine calculates the processing direction from the estimated processing route after starting the deposition process in step 2. In the height displacement measurement system comprising the use of crossed line beams, the Y-direction position ΔY_ϕ in an image used for height displacement measurement differs according to the measurement direction, as shown in **Fig. 2(c)**. Therefore, the measurement direction is estimated from the processing direction information in the NC in step 3. The height displacement measurement system calculates the height displacement at the Y-direction position ΔY_ϕ according to the measurement direction in step 4. The measurement position is the position of the crossed line beams on the processing route. The measured bead height is the height of the $(n-1)$-th layer, which is the previous layer. Hence, our proposed system can be used to measure the bead height of the previous layer in front of a processing spot on the processing route. The measured height displacement is sent to the NC machine, which controls the wire-feeding speed when the processing spot reaches the measurement position in step 5 such that the deposition height reaches

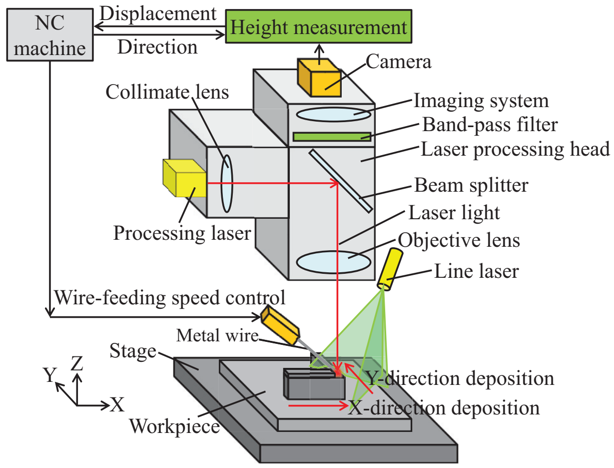

Fig. 5. Configuration of height displacement measurement system using crossed line beams for the laser metal-wire deposition.

the target value. Thus, the deposition of the target bead height is achieved in every layer by controlling the wire-feeding speed wherein the n-layer deposition is based on the measured height displacement of the $(n-1)$-th layer. The control value of the wire-feeding speed was estimated experimentally in advance from the relationship between the wire-feeding speed and bead height. In this system, the wire-feeding speed was controlled linearly based on the measured bead-height displacement. The other parameters, such as the power of the process laser and the scanning speed of the stages, were constant values without control. The NC machine judges whether the deposition of the N-layer is completed in step 6. If the deposition of the N-layer is not complete, the NC machine raises the Z stage. However, if the deposition of the N-layer is complete, the deposition is stopped.

3. Experiment Setup

In the following, the system configuration of the height displacement measurement system comprising the use of crossed line beams for laser wire DED is presented. We also show the optical design results for the in-process measurement during laser processing.

3.1. System Configuration

Figure 5 presents the experimental setup of our proposed height displacement measurement system comprising the use of crossed line beams for laser wire DED. Laser wire DED can be used to fabricate freeform shapes by moving a processing head relative to a workpiece using stages while feeding a metal wire obliquely (from the $-X$ direction) to the laser processing spot and irradiating a high-power processing laser. In this setup, the processing head has X, Y, and Z stages, and the workpiece is on a C-axis stage that rotates in the X-Y plane around the Z-axis. We used a general laser processing head and reflected a processing laser light onto the workpiece using a beam splitter. The reflected light was focused using an objective lens and irradiated onto the processing position. In the laser deposition process, we irradiated the processing laser light through a shielding gas nozzle to prevent metal oxidation. The metal wire was fed to the deposition position and melted using an irradiated processing laser. The deposition process was performed by scanning a processing head relative to a workpiece while the processing laser melted the metal wire. Furthermore, we integrated the imaging system of our proposed system into the processing head. We measured the height displacement using a coaxial setup of the laser processing axis because the objective lens used for the laser processing was shared with our proposed system. We attached the illuminating system of our proposed system to the opposite side of a metal wire on the side of the processing head and projected crossed line beams onto the workpiece. The reflected light from the workpiece surface was captured with an objective lens through the gas nozzle. Imaging system images reflected light that passed through a beam splitter onto a camera integrated with a processing head. Thus, we could coaxially measure the height displacement in front of the processing position based on the projected position of the line beam on the image captured by the camera. The design projection angle of the line beam was set as $\theta = 50^\circ$, transverse magnification of the imaging system was $M = 0.44$, and the camera pixel size was $P = 5.5$ μm, such that the displacement by the camera's 1-pixel ΔH is 15 μm according to Eq. (2). Furthermore, our proposed system can achieve both height displacement measurement and the monitoring of a melt pool with only one camera because our system measures the height displacement with a coaxial setup of the laser processing axis. Hence, it may be possible for our system to control process parameters based on both the in-process height displacement measurement results in front of the laser processing spot and the monitoring results of a melt pool in the future.

3.2. Optical Design for In-Process Measurement

The projection position of the line beam should be as close to the laser processing spot as possible for realizing an accurate height measurement. This would facilitate the estimation of the measurement direction using an NC machine when processing complex routes such as curves. In this setup, we designed the line beam's projection position at 0° and the ±90° direction at 4 mm from the laser processing axis center, as shown in **Fig. 6**, because the spot diameter of the processing laser was ϕ3 mm. In this case, the projection position of the line beam in the ±45° direction that is closest to the processing laser spot was 2.8 mm. Therefore, the height measurement range of our system was ±1.5 mm as per Eq. (1) because we could calculate a maximum centroid shift of 1.3 mm of the line beams on the camera image. This range is sufficient for measuring the height displacement for the laser process control because the height displacement from the target

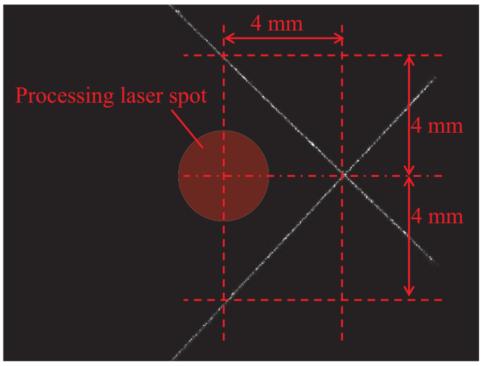

Fig. 6. Image of crossed line beams on a flat plane.

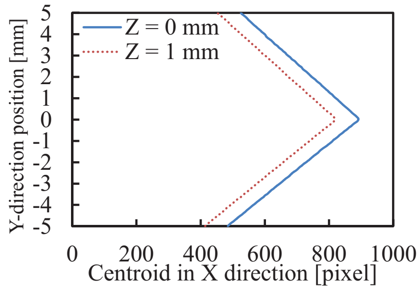

Fig. 8. Centroid position of crossed line beams on flat workpiece at $Z = 0$ mm and $+1$ mm.

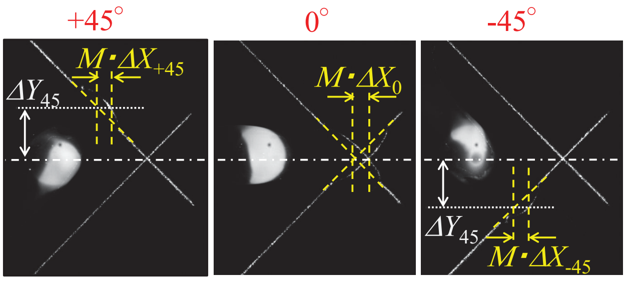

Fig. 7. Images of crossed line beams on a weld bead during laser processing at 0° and the ±45° direction.

height to the occurrence of a droplet or stabbing is almost 1 mm.

However, optical height displacement measurement becomes increasingly difficult owing to the influence of intense thermal radiation generated from the processing laser spot as the measurement position approaches the spot. Therefore, we inserted a 520 nm band-pass filter of the wavelength of the line beam into the imaging system to reduce the influence of thermal radiation with a broad spectrum whose center wavelength is infrared. Furthermore, we used 70 mW-power line lasers such that the luminance of the line beam was adequately high for thermal radiation. In-process camera images captured during laser processing by our proposed system for a weld bead in the 0° and ±45° directions are presented in **Fig. 7**. Our proposed system could capture the crossed line beams during laser processing without the influence of thermal radiation, which is similar to previous studies [25, 26], owing to the band-pass filter in the imaging system and optimization of the line beam's luminance. This result shows that our system obtained in-process height measurements during the laser processing. Furthermore, the projection position of the line beam was shifted in the Y-direction position of the center in the camera image when we measured the bead height in the 0° direction. Similarly, the line beam's projection position was shifted in the Y-direction position up and down $\pm\Delta Y_{45}$ from the Y-direction center of an image when we measured the bead height in the ±45° direction. Thereby, we can show that the line beam's projection position at the Y-direction position according to the measurement direction is shifted according to the height displacement, as designed. Consequently, our proposed height displacement system realized in-process height displacement measurement at positions from 2.8 mm to 4 mm in front of the processing laser spot within a ±90° measurement direction during the laser processing because we measured the height displacement based on the shift in the line beam's projection position at the Y-direction position according to the measurement direction. This means that our system can measure the height displacement at the physically nearest position from the processing laser spot of size $\phi 3$ mm.

4. Result and Discussion

First, we evaluated the height displacement by measurement direction on a flat metal workpiece as the height displacement measurement evaluation of our proposed system using crossed line beams. Next, we evaluated the height displacement accuracy using the measurement directions with a bead. Finally, we present the continuous deposition result with a complex processing route while changing the processing direction using laser wire DED to verify the laser process control.

4.1. Accuracy Evaluation

We present the height displacement measurement result obtained on changing the height of the flat surface. The centroid positions of the crossed line beams when the basic height ($Z = 0$ mm) and the processing head are moved 1 mm away are presented in **Fig. 8**. The crossed line beams are shifted in the $-X$ direction because the processing head was moved away from the workpiece. The displacement in the measurement direction is presented in **Fig. 9** and was estimated based on the difference between the measured height of $Z = +1$ mm and the basic height after the height was calculated from the centroid position. Our proposed system measured the height displacement within the ±90° measurement direction at an accuracy of less than ±50 μm. We could realize highly accurate height displacement measurements of a flat workpiece in the ±90° directions using the height measurement system with crossed line beams as the measurement accuracy is

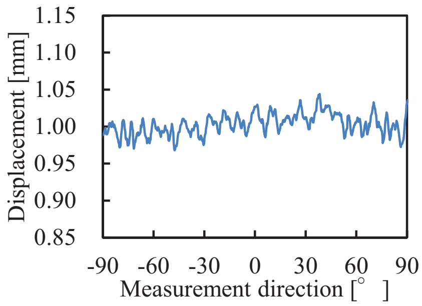

Fig. 9. Displacement by measurement direction on a flat workpiece when the processing head is moved from $Z=0$ mm to $Z=+1$ mm.

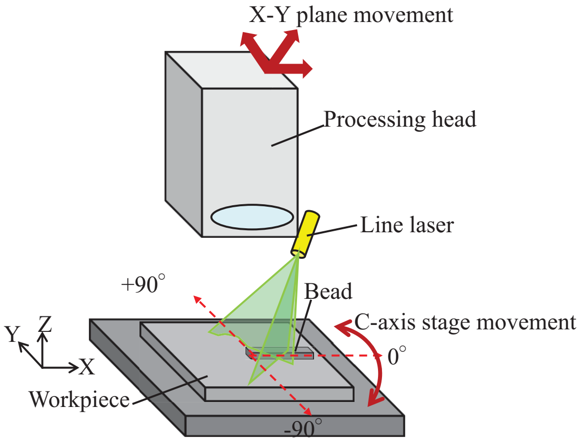

Fig. 10. Experiment setup of height displacement accuracy evaluation by measurement direction.

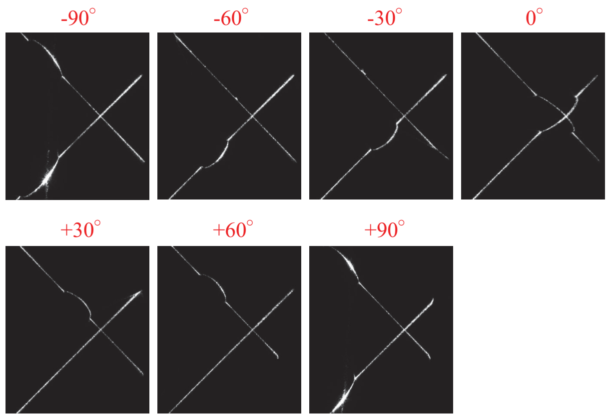

Fig. 11. Image of crossed line beams on a weld bead. Measurement directions are 0°, ±30°, ±60°, and ±90°.

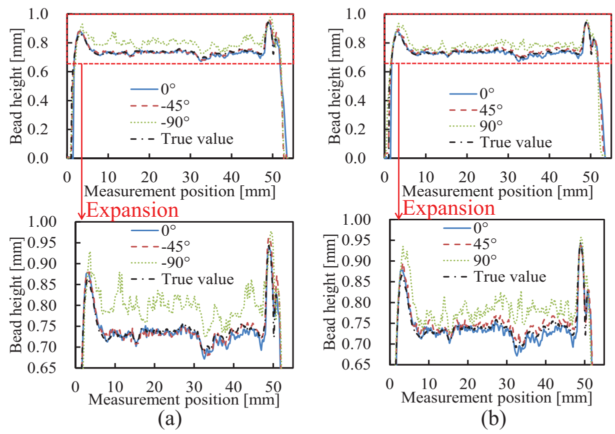

Fig. 12. Height measurement results of weld bead by measurement direction: (a) measurement directions are 0°, −45°, and −90° and (b) measurement directions are 0°, +45°, and +90°.

independent of the measurement directions.

Next, we presented the evaluated results of the height displacement measurement accuracy by measurement direction using a weld bead on a flat workpiece. In our proposed method comprising the use of crossed line beams, the Y-direction line beam positions used for the height displacement measurement are different from the measurement directions. Therefore, we evaluated the height measurement accuracy in the measurement direction using the same weld bead. The accuracy-evaluation experiment setup for our proposed system comprising the use of crossed line beams is presented in **Fig. 10**, wherein the processing optical system and imaging system are omitted. We set the workpiece with a 50 mm-long single-layer bead on the processing machine. We measured the bead height without laser processing in the measurement direction using the same weld bead at the C-axis stage with a weld bead and the X and Y stages with the height measurement system. We performed the evaluation without laser processing in this setup because the height displacement measurement results during the laser processing were the same as those without laser processing [25, 26]. We rotated the weld bead in the ±90° direction by the C-axis stage and scanned the height displacement measurement system along each measurement direction by scanning the X and Y stages. The images of the crossed line beams at the center of the measured weld bead in the 0°, ±30°, ±60°, and ±90° measurement directions are presented in **Fig. 11**. The shifted Y-direction position of the crossed line beams measuring the height displacement differed according to the measurement directions, as per design. The bead height results from the measurement positions calculated from these measured crossed-line beam images are presented in **Fig. 12**, wherein we considered the result of the optical non-contact height measurement instrument (NH-3N, Mitaka Kohki, Co., Ltd.) as the true value because its measurement accuracy was sufficiently greater than our proposed system. This instrument uses an auto-focus method with triangulation and uses the objective lens of a microscope for obtaining high-accuracy measurements. The measurement accuracy was ±1 μm, and the spot size was $\phi 2$ μm. **Fig. 12(a)** presents the results that measurement directions are 0°, −45°, and −90°, and **Fig. 12(b)** presents the results that measurement directions are 0°, +45°, and +90°. Our proposed system obtained bead shape measurements that were almost iden-

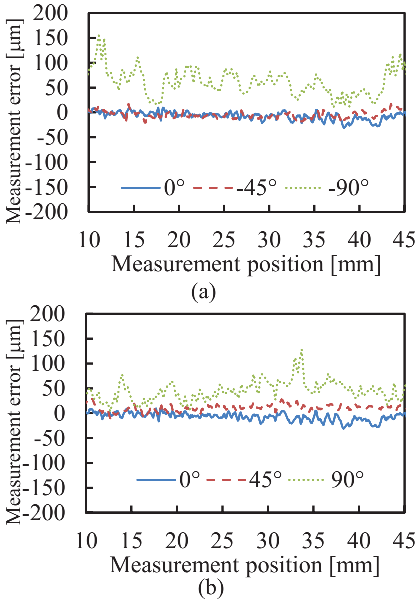

Fig. 13. Height displacement measurement error of a weld bead by measurement direction. The error was estimated from the difference between the measurement result and true value: (a) measurement directions are 0°, $-45°$, and $-90°$ and (b) measurement directions are 0°, $+45°$, and $+90°$.

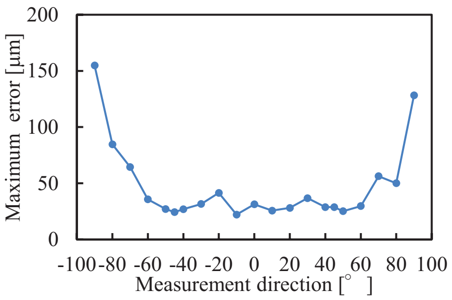

Fig. 14. Maximum measurement error of a weld bead by measurement directions. This result is averaging value in flat region ($X = 10$–45 mm) on a weld bead.

tical to the true value irrespective of the measurement direction, including the start and end points of the weld bead.

The height displacement measurement accuracy results estimated based on the difference from the true value are presented in **Fig. 13**. **Fig. 13(a)** presents the results that measurement directions are 0°, $-45°$, and $-90°$, and **Fig. 13(b)** presents the results that measurement directions are 0°, $+45°$, and $+90°$. This shows the result at a flat position ($X = 10$–45 mm) and not the start and end positions of the weld bead, which comprise a sharp slope. Furthermore, the maximum error to the true value based on the measurement directions (10° pitch) is presented in **Fig. 14**. The height displacement measurement accuracies for all the measurement directions within ±90° were less than ±150 μm, which is the target accuracy. The height displacement measurement accuracies of the measurement directions within ±60° were less than ±50 μm.

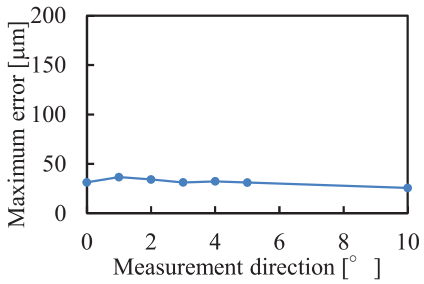

Fig. 15. Maximum measurement error of a weld bead at small angles of measurement direction as estimated by line beams near the intersection. This shows the expansion of **Fig. 14** in the range of 0°–10°.

This indicates that our proposed system can measure the weld bead height with a high accuracy irrespective of the measurement direction, which is similar to the case of a flat workpiece. In contrast, the maximum height displacement measurement accuracies of the measurement directions at greater than ±70° were ±150 μm owing of the regular reflected lights from the side of the weld bead. In the line beam images in the ±90° direction presented in **Fig. 11**, the light at the bead position had a high intensity and was glaring. Because the line beam that was projected from the $+X$ direction met the regular reflection condition on the sloped side of the weld bead lying along the Y direction, it was incident onto the imaging system as regular reflected lights and not as scattered light. The line beam width at the weld bead position on the image sensor increased in the $+X$ direction with the high-intensity light because the crossed line beams projected from the $+X$ direction were regularly reflected on the sloped side of the weld bead. As a result, the centroid positions of the line beams were calculated in the $+X$ direction. This means that the measurement error of the measurement directions at angles greater than ±70° became the plus value. The reflective characteristic of this regular reflected light depends on the shape and roughness of the side of the weld bead. Hence, the height displacement measurement accuracy varied locally depending on the measurement position. In the future, we intend to work to reduce the influence of regular reflected light for realizing more accurate measurements.

Furthermore, we present the height displacement measurement result near the 0° measurement direction, which is the intersection of the two line beams in **Fig. 15**. We evaluated the height displacement accuracy of the measurement directions from 0° to $+5°$ with a pitch of 1°. Our proposed system achieved an accuracy of ±50 μm even very close to 0°, where two line beams cross without accuracy deterioration. Consequently, the line section method using crossed line beams could measure the weld bead height with an accuracy of less than ±150 μm, which is the target accuracy irrespective of the measurement direction. Moreover, the measurement accuracy, especially within the ±60° measurement direction, was less than ±50 m, which is the same as that of a flat workpiece.

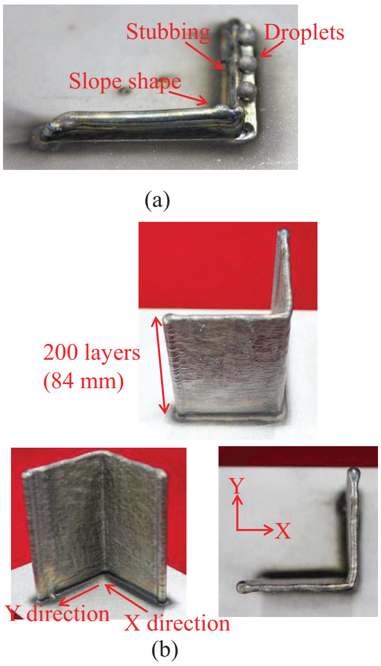

Fig. 16. Continuous deposition results for "L" shape: (a) without laser process control and (b) using laser process control.

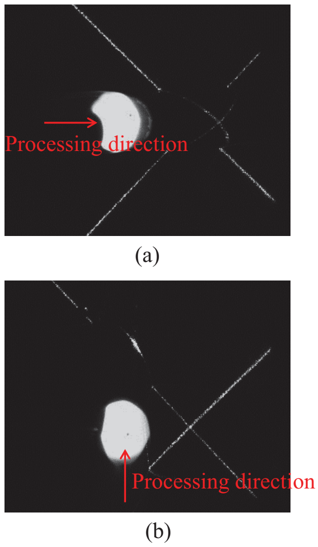

Fig. 17. In-process images of crossed line beams: (a) in X-direction deposition and (b) in Y-direction deposition.

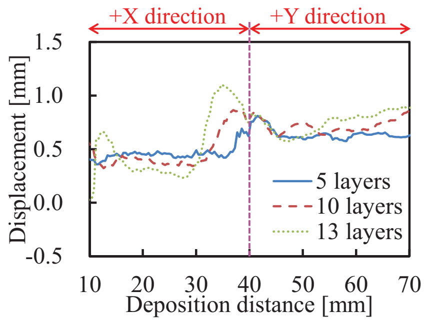

Fig. 18. Height displacement results by deposition distance without laser process control.

4.2. Process Control Evaluation

We evaluated the continuous deposition evaluation process with and without process control to determine the effectiveness of our wire-feeding speed control system based on the in-process height displacement measurement result obtained using crossed line beams. In this evaluation, we implemented the continuous deposition of an "L" shape using laser wire DED as the deposition processing route changed the processing direction. We scanned the processing head along the processing route of the "L" shape relative to a workpiece using the X and Y stages with the processing head. We changed the processing direction after a 40 mm deposition in the $+X$ direction and implemented 40 mm deposition in the $+Y$ direction. Furthermore, we raised the processing head using the Z stage with the processing head after every single-layer deposition.

We present the continuous deposition results obtained for the "L" shape with and without process control in **Fig. 16**. The metal wire used in this experiment was Inconel. The shape near the right-angle position that changes the processing direction is the slope presented in **Fig. 16(a)** because of the acceleration and deceleration of the stage when the conventional method is used without laser process control. Moreover, the continuous deposition must be stopped after 13 layers owing to the formation of droplets during the $+Y$-direction deposition after the processing direction is changed. The side of the bead was shaved during $+Y$-direction deposition because an excess amount of the metal wire was fed from the $-X$ direction. However, we realized a continuous deposition of more than 200 layers (approximately 84 mm) for creating a complex shape in which the processing direction was changed by the laser process control, as shown in **Fig. 16(b)**. We present the images of the crossed line beams during the $+X$- and $+Y$-direction depositions in **Fig. 17**. **Fig. 17(a)** presents the images in the X-direction deposition, and **Fig. 17(b)** presents the images in the Y-direction deposition. Thus, the laser process control for the complex processing shape can be realized by measuring the height displacement in front of the processing spot during the laser processing according to the processing direction. The shape at the right-angle position that changes the processing direction from the $+X$ direction to the $+Y$ direction was flat, which is similar to the shape at the straight processing position, despite the acceleration and deceleration of the stage. Furthermore, both $+X$-direction deposition and $+Y$-direction deposition could fabricate the same flat shape, although the metal wire-feed direction toward the processing direction was different.

The height displacement measurement result with respect to the deposition distance without laser machining control is presented in **Fig. 18**. The results at deposi-

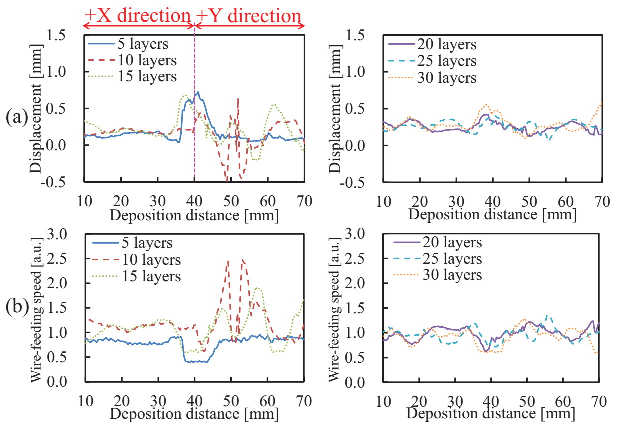

Fig. 19. Height displacement results and wire-feeding speed by deposition distance with laser process control: (a) height displacement measurement results and (b) controlled wire-feeding speed results.

Accordingly, we clarified that the laser process control of a complicated shape in which the processing direction changes could be realized by the height displacement measurement system comprising the use of crossed line beams, although the influence of a change in the laser process environment, such as the temperature change due to heat storage, was significant immediately after the deposition started. Moreover, highly accurate continuous deposition became possible, even when the machining direction changed after the laser process environment became stable because the wire-feeding speed could be controlled based on the in-process height displacement of the deposition object with laser process control. In addition, the deposition accuracy for the complicated shape, for which the deposition direction changed, could be improved by using laser process control although acceleration and deceleration of the stage occur and the deposition direction toward the metal wire-feeding direction changes.

tion distances from 10 mm to 70 mm are presented in the figure, except for the start and end positions. The deposition distance from 10 mm to 40 mm was the result of $+X$-direction deposition, and the deposition distance from 40 mm to 70 mm was the result of $+Y$-direction deposition. We presented the results of the 5th and 10th layers and the result of the 13th layer just before the end of the continuous deposition. The deposition height displacement without laser process control near the 40 mm deposition distance, which is a right-angle position where the deposition direction changes, increased as the continuous deposition progressed owing to the acceleration and deceleration of the stage. Similarly, we present the height displacement measurement result and the wire-feeding speed control result during the continuous deposition with the laser process control in **Fig. 19**. **Fig. 19(a)** presents the height displacement measurement results, and **Fig. 19(b)** presents the controlled wire-feeding speed results. These results showed up to the 30th layer at the deposition start every five layers. Although the deposition height displacement changed significantly around the 40 mm deposition position where the deposition direction changed and during $+Y$-direction deposition between the deposition start and the 15th layer, the wire feeding speed was controlled based on the in-process height displacement results. The wire feeding-speed control amount might not be optimal for the change in the laser process environment because the wire feeding-speed control amount in this experiment was linear, as in [25, 26], although the heat storage started and the laser process environment changed at the start of the deposition. The method of dynamically changing the control amount based on the bead's temperature and the measured height displacement is considered as the solution. Furthermore, deposition with ± 0.25 mm height displacement was possible using laser processing control, including at the right-angle position where the processing direction changed because the laser process environment became stable during the deposition of more than 20th layers.

5. Conclusions

We proposed a line section method comprising the use of crossed line beams for realizing laser process control when laser processing along a complicated processing route changes the processing direction. This method can be used to measure the height displacement in front of a laser spot in the $\pm 90°$ direction. In this system, the two crossed line beams were projected from the side of the processing head, and the height displacement was measured using the light-section method. The characteristics of the height displacement measurement system using crossed-line beams are presented below.

- Our system could measure the height displacement in front of a laser processing spot within the $\pm 90°$ direction during laser processing with a simple configuration comprising the addition of a single line laser to the conventional light-section method.
- The height displacement was estimated using a simple calculation process because the centroid shift of the crossed line beams in an image when the height changes was in the same direction irrespective of the measurement direction.
- The configuration of our proposed system was compact because the imaging system was integrated into a laser processing head.
- We measured the height displacement at 2.8–4 mm in front of a laser processing spot during laser processing according to the measurement directions by reducing the influence of intense thermal radiation.

We evaluated the height displacement measurement accuracy in the measurement direction for our proposed system. The height displacement in the measurement direction was measured by rotating the same weld bead in each measurement direction. We achieved a target height displacement measurement accuracy of less than ± 150 μm for all the measurement directions within $\pm 90°$. The measurement accuracies, especially within $\pm 60°$, were less than ± 50 μm, which is the same as the measurement accuracy obtained for a flat workpiece. Meanwhile, the height displacement measurement accuracies in the measurement directions at angles greater than $\pm 70° \sim \pm 90°$ were ± 50 μm in the case of a flat workpiece. However, the measurement accuracy was ± 150 μm owing to the regular reflected lights from the side of the weld bead in the case of a weld bead. In the future, we intend to work to reduce the influence of regular reflected lights for obtaining more accurate measurements. Solutions to this issue include using a configuration such that the projected line beams are not reflected from the side of the weld bead or improving the centroid calculation algorithm for height displacement measurement. Consequently, we realized both a compact configuration and height displacement measurement within the $\pm 90°$ direction with our line section method with crossed line beams. This system can also be used to measure the 360° direction by projecting an additional crossed line beam from the opposite side.

Furthermore, we evaluated laser process control in a complicated processing route in which the processing direction changes while using laser wire DED in a metal AM machine. We presented the configuration of the wire-feeding speed control system based on the measured height displacement, where the height displacement in front of a laser processing spot in the measurement direction estimated by the NC machine was measured using the line section method with crossed line beams. We evaluated an "L" shape continuous deposition in which the deposition direction changed from the $+X$ direction to $+Y$ direction with and without laser process control. The continuous deposition must be stopped after 13 layers in the conventional method without laser processing because the shape near the right-angle position changes the processing direction and raises the slope because of the acceleration and deceleration of the stage. In contrast, we realized a continuous deposition of more than 200 layers (approximately 84 mm) with laser process control based on the in-process height displacement result in the measurement direction estimated from the processing route using an NC machine. The shape at the right-angle position that changes the processing direction from the $+X$ direction to the $+Y$ direction was flat, which is similar to the shape at the straight processing position. As a result, highly accurate continuous deposition could be realized without increasing the measurement time with laser process control based on the in-process measurement result of the height displacement in front of the laser processing spot, even for complicated shapes that comprise processing direction changes. This method may be applied to in-process height displacement measurements for deposition during five-axis processing to fabricate more complicated shapes. Our future work will be focused on realizing process control in five-axis deposition in metal AM.

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