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ORIGINAL ARTICLE

One-axis on-the-fly laser system development for wide-area fabrication using cell decomposition

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Abstract We have developed a one-axis on-the-fly system that can continuously process a large area by using a laser scanner. Existing laser processing using scanner systems can be used for precision processing, but have a limitation in the area of processing. To supplement this shortcoming, a step and scanning technique using a stage has been developed. This technique can process a large area in such a way that, after laser processing, the stage moves repetitively; however, this method has a demerit in that processing quality in the part between the scan areas is not even. To solve this problem, there is a method of synchronizing the scanner and the stage. This study developed an on-the-fly system that synchronizes the one-axis stage and the two-axis scanner. Also, in synchronized processing, the velocity of the stage due to the velocity of fabrication is very important. If the velocity of the stage is not proper, the laser processing deviates from the scanner work area. We proposed an algorithm in which, using a cell decomposition method, the velocity of the stage is automatically calculated by compensating for the acceleration/deceleration time occurring in the stage rotation and the reverse rotation due to the velocity of the fabrication. We compared the step and scanning method to the on-the-fly method through a low-frequency experiment and proved that the latter has better precision for the boundary of the scan area; we further analyzed the precision by using a large area marking and an overlapping experiment. In addition, by measuring encoder output signals, a compensation algorithm for the stage acceleration/deceleration time was verified.

Keywords Laser scanner · Stage · On the fly · Synchronization

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1 Introduction

With recent laser micromachining process technologies, it is possible to obtain high focus and precise spatial and temporal control of the laser beam. Therefore, these processes have been used widely as a technology that may enable processing of high-quality parts in fields such as advanced semiconductors, electronics, automobiles, and mechatronics. In addition, the process is environmentally friendly, and it contributes to the development of new, noncontact processes in the field of machining parts with micrometer sizes. In particular, laser sources and technological developments in the field of laser applications using short-pulse lasers have contributed to developments in the automotive industry and in the fields of solar cells, displays, and electronic components. Examples that are applicable to lasers in these industries include via-hole drilling [1], FPCB cutting [2], and laser surface patterning [3]. The trend of laser fabrication requires high speed, wide area, and dry processes that take environmental costs into consideration. Galvanometer scanners have been widely used as marking tools [4]; recently, these scanners have been applied in many laser material fabrication fields [5]. However, the working field size of a galvanometer scanner is limited by the focal length of the f-theta objective lens, which is measured from the scanner head to the sample. With any increase in the focal length, the working field size of the scanner widens but the resolution decreases, which can be a significant drawback to precise fabrication. Therefore, a hybrid method that involves the use of both a linear stage and a scanner has been considered for wide-area fabrication. The initial hybrid approach adopted is known as the step and scanning method. In this method, the stage moves and stops one step away; then, the scanner operates when the stage stops. This action is repeated over the area being marked. Therefore, this approach cannot accomplish continuous scanning laser processing, and its precision decreases at the processing area boundaries. Furthermore, this approach has a disadvantage in that it requires a significant amount of time compared to the continuous laser processing. Recently, an on-the-fly method has been used to modify the step and scanning method. The on-the-fly method is a control method in which the scanner and stage are synchronized. In this way, the stage moves continuously, and the accuracy of the border development is high. This new method can also cause an elevation of the processing quality due to the increased processing speed. Currently, laser processing equipment companies that can support on-the-fly methods are ESI, LPKF, AEROTECH, and several others. The HDI 5330 model of ESI Inc. ensures an accuracy of ±20 μm for an area of 533 × 635 mm; its drilling system can process at a maximum speed of 500 mm/s. The MicroLine 6000 model, produced by LPKF Inc., was also launched recently; it has been applied to the cutting of materials such as Coverlayer, Printed Circuit Board (PCB), and Flexible Printed Circuits (FPC). Its work area is 533 × 610 mm, which is similar to that of ESI's product; its precision is also within ±20 μm. The processing path is generated using LPKFCAM software. Thus, a reduction of approximately 20 % is demonstrated in the cutting time. Aerotech Inc. (USA) has released an on-the-fly module for the step and scanning method. Furthermore, RAYLASE and SCANLAB from Germany have presented machines that can synchronize the stage and scanner control board. With both of these products, it is possible to synchronize the stage and scanner. However, the main application areas of the developed boards have been laser marking, such as that used for liquid crystal display (LCD) panels for large-area electronic parts; these have been limited to the purpose of such markers. In addition, since laser marking involves processing using G-code, nonexperts have difficulty in using it, and the system has a demerit in that it takes a long time for coding if there is a lot of data. The methods proposed in this paper can be used to obtain continuous processing on a large area by synchronizing the scanner with the stage. Compared to that of the existing step and scanning method, the precision when using this method is even and the velocity of the fabrication is fast. In addition, users do not have to enter G-code because the velocity of the stage is automatically calculated and entered from CAD. Since the scanner and the stage have been synchronized, the velocity on one side affects the velocity on the other side. Since the scanner processing area is limited, the correct processing is possible when the velocity of the stage is properly controlled. We proposed an algorithm that automatically calculates the velocity of the stage by dividing the work area by using the *cell decomposition* method. In addition, the time delay occurring in the rotation and reverse rotation of the stage were compensated for in order to apply this method to a one-axis stage. A scan board and the marking on-the-fly (MOTF) method necessary for synchronization has been developed to design the system. By using a low-frequency laser, we proved the superior quality of the on-the-fly method compared to the step and scanning method; errors from the CAD data were measured after processing a large area by using the on-the-fly technique. Also, through stage and galvanometer signal measurements, we checked that the processing was correct using the proposed algorithm.

2 One-axis system design for on-the-fly control methods

2.1 System configuration

Figure 1 shows the configuration of the on-the-fly system. The system for configuring an on-the-fly machine is divided into three parts. The first is a scanner system that can be marked. The digital signal that is ordered from the scan board is converted into an analog signal, which is passed to the driver of the galvanometer. The attached two-galvanometer mirrors are driven by a signal. The two mirrors of the attached galvanometer are driven by the signal. The second is the control unit, and again, this part consists of three kinds. The scan board is responsible for functions related to the movement of the galvanometer mirrors and for the on/off function of the laser. The MOTF board is responsible for synchronizing the scanner and the stage. This board receives a stage position signal and delivers it to the scan board. The motion board is responsible for the movement of the stage. Finally, the stage-part consists of a one-axis linear motor. We have developed a scanner board and MOTF board. A DSP chip with a frequency of 150 Mhz was used by the scanner board; the sampling rate of the scanner board is 30 μs. Finally, the motion board has a sampling rate of 1 ms.

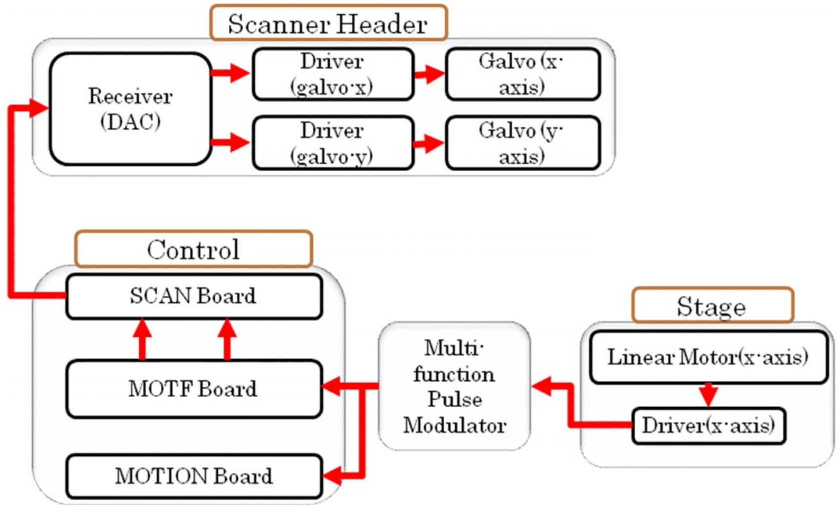


Fig. 1 System configuration

2.2 Synchronization technology

In the past, the step and scanning method was used. A stage repeats its movements and stops in a step-wise manner; a scanner begins to work when the stage stops. By using this method, it is possible to process a large area with even precision. However, it is necessary to synchronize the stage and the scanner because if this is not done, there is no guarantee of uniformity in the joints. Figure 2 shows the synchronization for the on-the-fly method, represented by block diagrams. As can be seen in the figure, the CAD data that has been entered is divided into two parts. First, the scale of CAD data conversion is required because the actual processing length is different according to the movement of the mirrors. Again, this signal can be compared with the signal coming from the stage. The encoder signal of the stage is converted to the required scale in order to move the mirrors. This signal that will move the mirrors is transmitted to the driver of galvanometer. Second, the speed and direction of the stage are determined using a cell decomposition algorithm. For the scanner and the stage to be synchronized, and in order to keep the velocity of the fabrication constant, an appropriate stage velocity is required. This paper applied an algorithm in the form of the velocity distribution by using the cell decomposition algorithm. The velocity information for each section obtained in this way is entered into the stage. Descriptions of this algorithm will be provided in the next chapter.

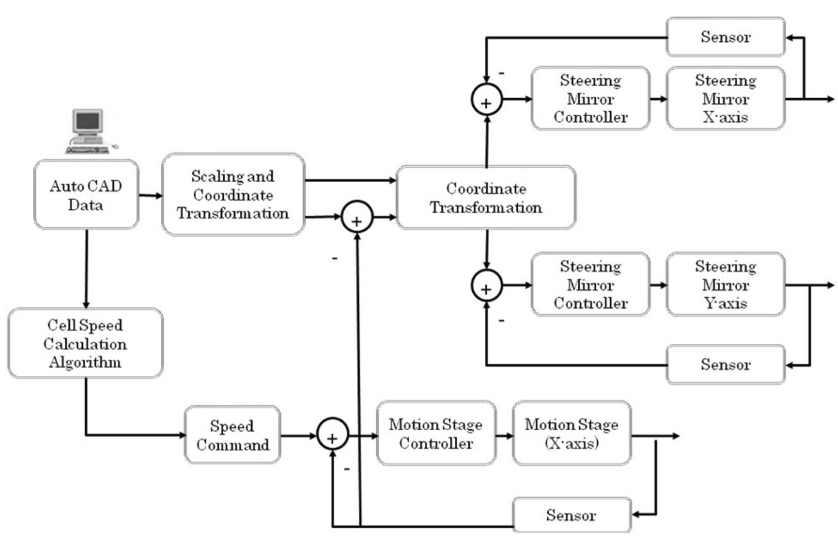


Fig. 2 System block diagram of the on-the-fly method

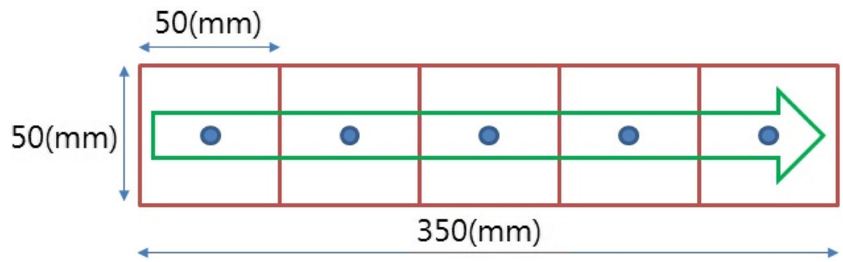


Fig. 3 Processing path using the cell decomposition

2.3 Stage speed calculation algorithm

2.3.1 Synchronization of the velocity distribution using cell decomposition

Since an on-the-fly system synchronizes the scanner and the stage, it should assign to the stage a velocity that fits with the command velocity of the fabrication. We studied a new synchronization method for the velocity control; our method uses a path plan algorithm. The question of the path plan is how to find a way to safely move without any collisions with obstacles from the starting point to the destination in a given space; this problem is dealt with in various areas such as computer graphics, artificial intelligence games, biotechnology, virtual environments, prototype production, operation demonstration, and CAD systems, as well as by robots, in various ways. Such path plan algorithms include bug algorithms and their varieties and the vector field histogram method. There are methods such as one using Voronoi diagrams, a method using a potential field function, methods that use stochastic sampling, one method that uses a visibility graph, and one method that uses a cell decomposition algorithm. Among these, we are using the cell decomposition algorithm. A cell decomposition algorithm is a method of subdividing empty spaces excluding obstacles in a given space in a particular method and forming a graph that connects the centers of each space to the centers of neighboring spaces in order to find the shortest path on that particular graph. Cell decomposition algorithms are subdivided depending on the method of dividing the spaces. The exact cell decomposition (ECD) algorithm is a method of dividing spaces other than obstacles by drawing a vertical line that passes each apex of a polygonal obstacle to the top or bottom boundary or that passes a point in contact with another obstacle. Each passage is farthest away from nearby obstacles, allowing the determination of a safe pathway. And yet, this method can only be applied if there is a polygonal obstacle. The grid cell decomposition (GCD) algorithm is a method of dividing an entire space into grids with regular size and then dividing the subdivided spaces into obstacle areas, empty space areas, and mixed areas in order to form a graph between the empty space areas. If the size of the grids is too small, a lot of memory space is required to contain the information about each space; on the other hand, if the space is too large, there may be a problem in that a passage that can connect between obstacles can become blocked. The adaptive cell decomposition (ACD) algorithm is a method of repeating in order to hold together four adjacent areas that have the same property in a grid space that has been minutely divided by GCD; this algorithm forms a graph between empty space areas after reducing the numbers of areas. Compared to GCD, the numbers of the areas involved when using this method becomes much fewer, so the entire space can be expressed more effectively. Among these methods, we used the GCD algorithm to divide the processing areas into grids with regular size. Since the size of the scan area is 50 mm, grid cell decomposition was applied at intervals of 50 mm. In addition, as can be seen in Fig. 3, the central point of each cell is found and the points are connected; this becomes the processing path,

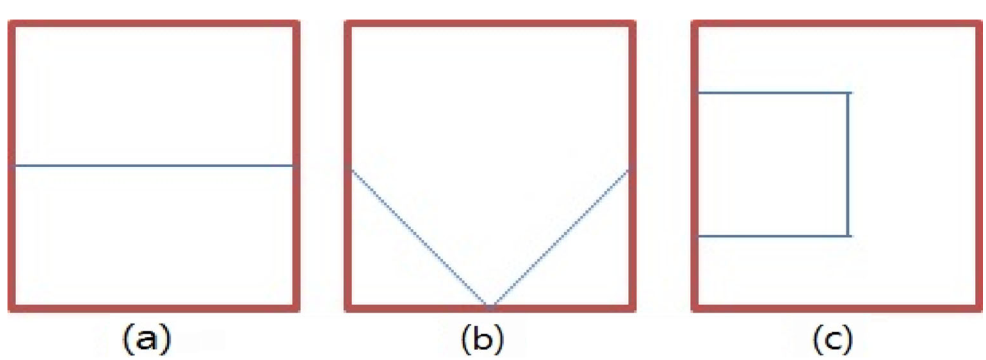
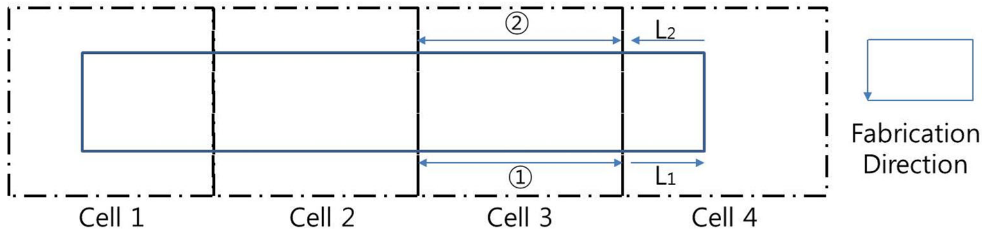


Fig. 4 Various laser processing paths

Fig. 5 Example figure for acceleration and deceleration compensation of the motor



that is, the stage movement. Next, we calculate the velocity of the stage according to the commanded velocity of the fabrication. What is most important in an on-the-fly system is that the velocity of the fabrication should be constant. If the velocity of the fabrication is not constant, the line width of the processing becomes unbalanced, which affects the quality of the processing. For the velocity of the fabrication to be constant, the vector sum of the scanner and the stage velocities should be the same as that of the velocity of the fabrication. Equation 1 shows the relationship among the velocity of laser processing (V_f), that of the scanner (V_{sc}), and that of the stage (V_{st}). Equation 2 shows the velocity of the cells divided by cell decomposition.

$$\dot{V}_f = \dot{V}_{st} + \dot{V}_{sc} \tag{1}$$

$$V_{cell} = \frac{L_{ref}}{L_{cell}} \times V_f \tag{2}$$

where,

$\dot{V}_f$: velocity of the fabrication

$\dot{V}_{st}$: velocity of the stage

$\dot{V}_{sc}$: velocity of the scanner

V_{cell} : velocity of per cell

L_{ref} : length of the reference

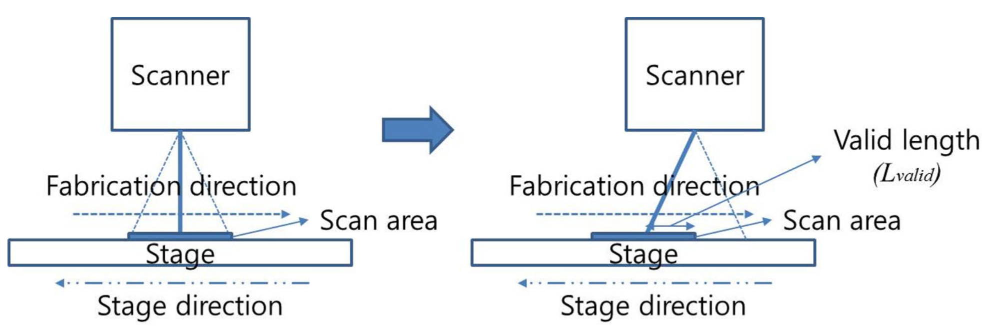
L_{cell} : fabrication length per cell

Figure 4 shows CAD to be processed on the divided cells. The length of the x-axis of the cells shown in Fig. 4a is 50 mm, while the length of the CAD to be processed is also 50 mm. Thus, the velocity of the fabrication and the velocity of the stage should converge. If we suppose that one cell is a reference cell when the command arrives, the velocity of the fabrication and the velocity of the stage are the same. Then, since the process shown in Fig. 4b is longer than that shown in Fig. 4a, the velocity of the stage should drop. By using Eqs. 1 and 2, the velocity of the stage of the cells can be obtained. The velocity obtained in this way is delivered as an instruction value of the stage. However, in Fig. 4c, it can be seen that the stage movements must be processed in a direction normal to the reverse direction. The impact of acceleration/deceleration should be compensated for. The next chapter will describe the method of compensation.

2.3.2 Compensation method of the acceleration and deceleration

By using the data presented in Fig. 4c, we can find the velocity of the stage of the relevant cells with Eq. 2; however, since the stage must perform rotations and reverse rotations, it should be faster than the calculated velocity of the stage. In this case, the synchronized velocity should be reassigned by cell decomposition in consideration of the motor acceleration/deceleration time. Suppose that we process a rectangular shape, as shown in Fig. 5. The processing area is cell decomposed, and by using Eq. 2, the velocity of the fabrication of each cell is calculated. However, as the last cell, cell 4 in Fig. 5, and for cells in which the stage direction changes from L_1 to L_2, to compensate for acceleration/deceleration time due to the acceleration/deceleration of the motor generated in cell 4, the velocity of cell 3 should be raised to a higher value. Velocity compensation

Fig. 6 The maximum valid length for speed compensation



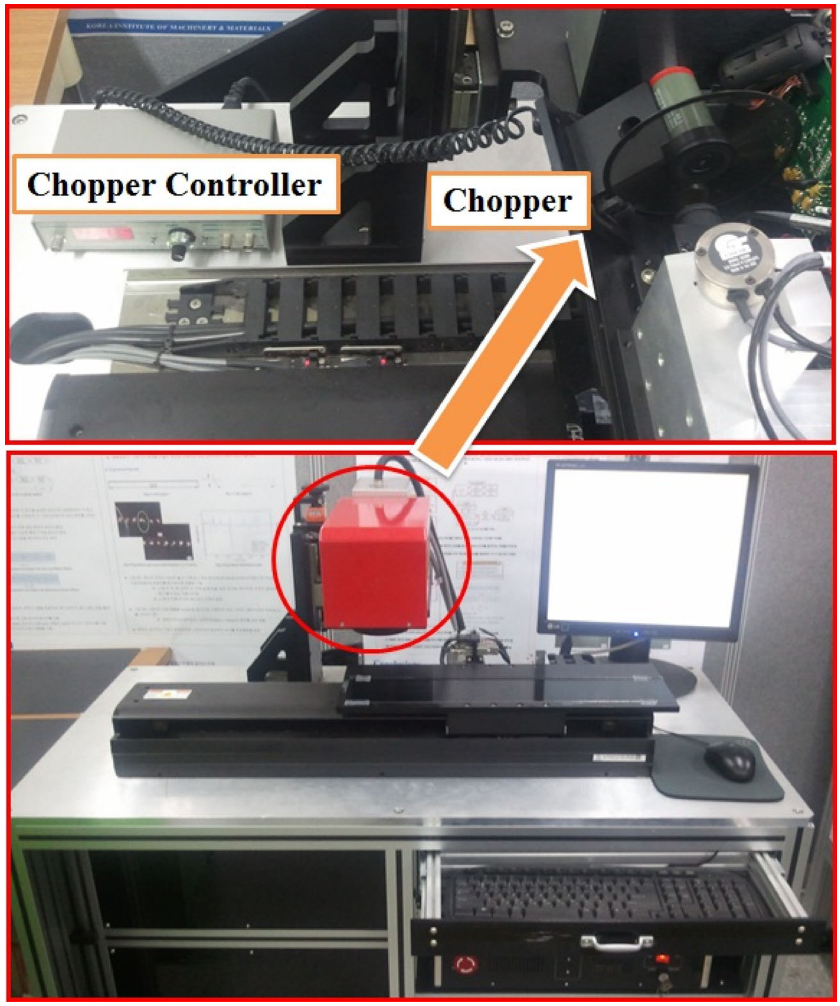


Fig. 7 The photo of one-axis stage–two-axis scanner on-the-fly system

is a method of compensating for the velocity of the entire set of cells with opposite velocity; if the compensation is too great, the scanner-stage synchronization does not match, and so correct processing is not obtained. So, the maximum velocity necessary to compensate should be determined. Figure 6 shows the length that can be compensated for in cell 3. The velocity of the stage can be raised to a velocity fitting with this length. In normal processing status, the laser is positioned at the center of the scanner processing area, as shown in the left image in Fig. 6. If the velocity is

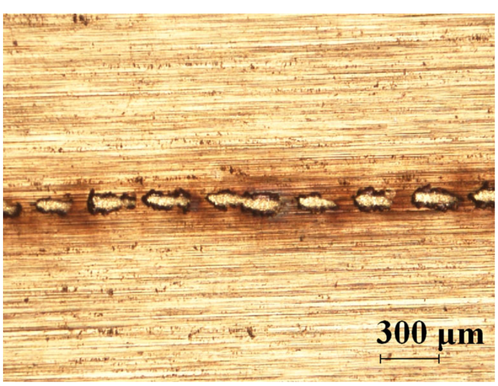


Fig. 8 The results of laser marking pattern using the step and scanning method

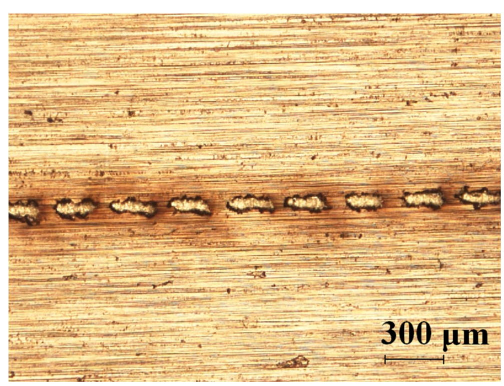


Fig. 9 The results of laser marking pattern using the marking on-the-fly method

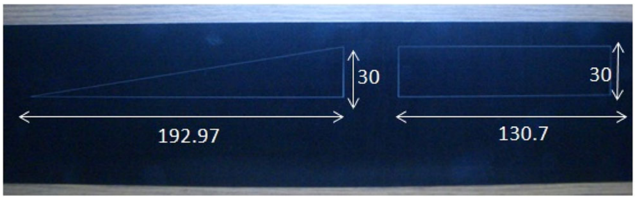


Fig. 10 Drawing results obtained from the on-the-fly system (unit in mm)

further raised in order to compensate for the stage acceleration/deceleration, the laser can be positioned at the edge of the scanner processing area. This is called a valid length of compensation. If it exceeds this range, correct processing cannot be performed. Thus, the velocity of the stage compensated for is as shown in Eq. 3, and this velocity may differ depending on the valid length. As shown in the right image in Fig. 6, the valid length is the maximum compensation of the velocity viewed until the point at which the laser is positioned at the edge of the scanner area. This compensation for the velocity is determined in consideration of the acceleration/deceleration time and the valid length of the stage.

$$V_{\mathrm{com}} = (L_{\mathrm{valid}} + L_{\mathrm{s}}) \times \frac{V_{\mathrm{f}}}{L_{\mathrm{s}}} \quad (3)$$

where,

V_{com} : velocity of the compensation

L_{s} : x-axis length of the scan area

L_{valid} : valid length

V_{f} : velocity of the fabrication

Table 1 Measurement data for right triangle drawing

Right triangle side	Error between the CAD data (μm)		
Fabrication speed (mm/s)	100	200	300
Height (10 times average)	77	66	76
Bottom (10 times average)	60	54	49
Hypotenuse (10 times average)	51	52	50
Average	62.67	57.34	58.34

Table 2 Measurement data for rectangle drawing

Rectangle side	Error between the CAD data (μm)		
Fabrication speed (mm/s)	100	200	300
Bottom (10 times average)	57	53	47
Right (10 times average)	68	55	66
Left (10 times average)	72	68	78
Top (10 times average)	60	55	47
Average	64.25	57.75	59.5

Table 3 Measurement data by the iteration

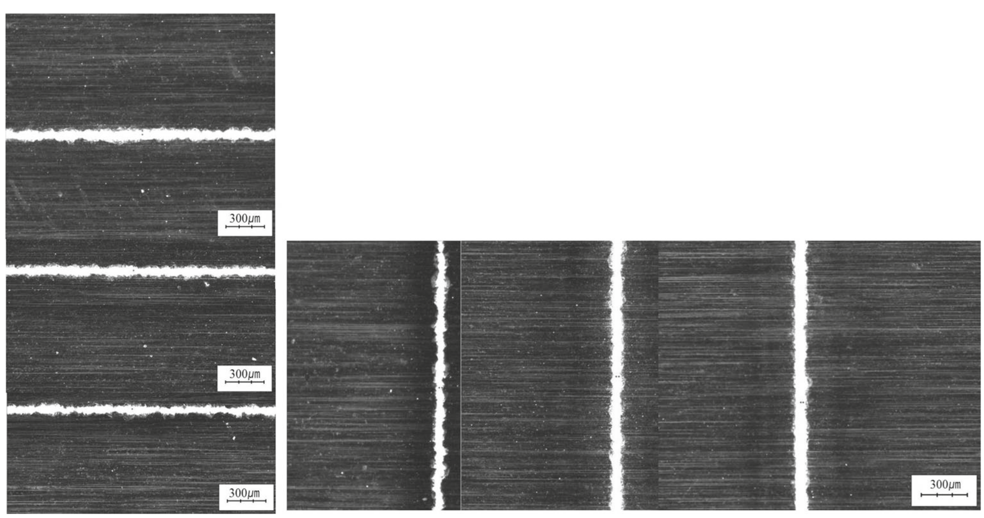
Number of fabrication	1	2	3
Horizontal error (μm)	47	49	49
Vertical error (μm)	72	75	78

3 Experiment

3.1 Comparison of step and scanning with on-the-fly method

A scanner control board that can accept two-axis stage signals is still under development. Only a one-axis stage/two-axis scanner on-the-fly system has been developed and

Fig. 11 Line width for the number of fabrication (*horizontal and vertical*)



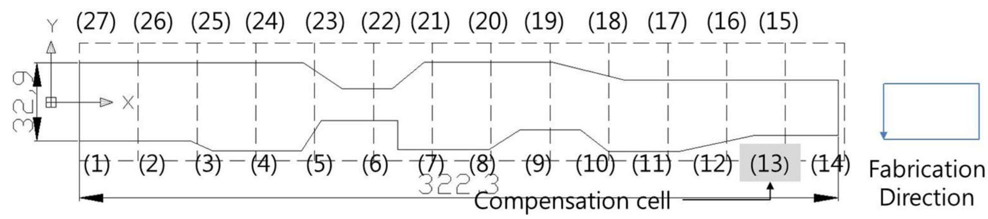


Fig. 12 CAD sample for a speed calculation algorithm (unit in mm)

tested in the current research, as shown in Fig. 7. An IPG fiber laser with a 30-ns pulse width, 12-W power, and 1,064-nm wavelength is used for the on-the-fly marking experiment. A CTI scanner head with an aperture of 10 mm and a focal length of 100 mm was used. The stage of the DASAROBOT has a 400-mm stroke with a maximum speed of 500 mm/s; straightness is ±21 μm, flatness is ±19 μm, and position repeatability is ±1 μm. After tuning the laser frequency to 1 kHz, we used a mechanical chopper to compare the step and scanning method to the on-the-fly method. The marking velocity was 300 mm/s, and the scanners work area is 50 mm × 50 mm. In the step and scanning method, while the scanner processes the work area, the stage does not move. After the processing, the stage moves 50 mm to the next area. As this movement is repeated, it processes a large area. In the on-the-fly method, the scanner and the stage move simultaneously. Since the scanner and the stage have been synchronized, processing can be performed if the velocity of the stage is properly controlled. We used the previously proposed algorithm to automatically enter the velocity of the stage. Processing specimen is an anodized aluminum plate with a thickness of 0.5 mm. Figures 8 and 9 show, respectively, the results of processing in the step and scanning and in the on-the-fly methods. The samples shown in Figs. 8 and 9 have the same marking length since the processing was performed using a frequency of 1 kHz. And yet, in Fig. 8, it can be seen that there is an overlapping processing line in the middle. This shows that the quality between the scanner areas is not even. In contrast, Fig. 9 shows that all the intervals between the scanner areas are constant. This shows that the on-the-fly method has a constant quality of processing.

3.2 Precision test of the on-the-fly system

The precision of the on-the-fly system is evaluated with the help of a drawing experiment (Fig. 10). A right triangle and a rectangle whose sizes are larger than the scanner working area are first drawn. Then, the length of each side of the images shown in Fig. 11 is measured and compared with the original CAD data. Ten samples were made; each side of the average of the measurements is shown in Tables 1 and 2. Also, three drawing speeds (100, 200, and 300 mm/s) are selected in order to test the influence of the speed. The size difference in the triangle drawing is approximately 60 μm, which is measured at three different drawing speeds. The drawing accuracy of the rectangle shows almost constant values. In addition, the different drawing speeds do not affect the precision of the drawing. This result may indicate that the precision in this case is conserved with various fabrication speeds for the on-the-fly system. In order to measure the length of a large area, measurements used QuickVision of Mitutoyo, both of which has less than 2-μm precision.

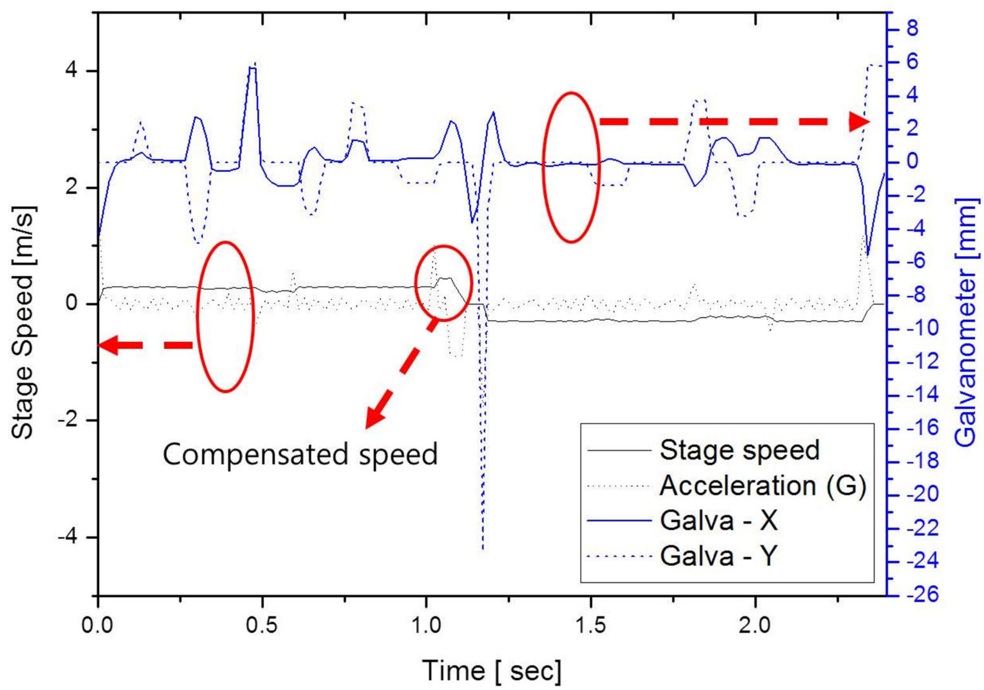
3.3 Overlapping through repeated processing of on-the-fly system

We have performed repeated processing of CAD in the same shapes to measure the repeated precision of the processing position. The shape chosen was a rectangle with a width of 200 mm and a height of 30 mm. The processing specimen was an anodized aluminum plate, and the velocity of the fabrication was 300 mm/s. With processing repeated three times, the line width and vertical width

Table 4 Stage speed command entered in cells

Position	1	2	3	4	5	6	7	8	9	10
Speed (m/s)	0.3	0.3	0.3	0.3	0.27	0.28	0.22	0.3	0.3	0.3
Position	11	12	13	14	15	16	17	18	19	20
Speed (m/s)	0.3	0.3	0.45	0.3	0.3	0.3	0.3	0.28	0.3	0.25
Position	21	22	23	24	25	26	27			
Speed (m/s)	0.3	0.22	0.22	0.3	0.3	0.3	0.3			

Fig. 13 Experiment closed-loop results



were compared, with results as shown in Fig. 11. Figure 11 shows measurements obtained through a microscope for the outcomes of one-time processing, two-time repeated processing, and three-time repeated processing. The left image in Fig. 11 is the horizontal width and shows the outcomes of the one-, two-, and three-time repeated processing, upwards; while the right image shows the outcomes of the vertical line width of the one-, two-, and three-time repeated processing, from left to right. If the repeated precision of the processing position is not even, the line width will differ. We measured the horizontal and vertical lengths of the rectangle centering around the center of the line width in order to compare the resulting values with the CAD data. The values measured in this way are shown in Table 3. In the results of the measurements, the repeated precision of the processing position has been found to have hardly changed.

3.4 The velocity calculation algorithm test

We tested the proposed algorithm with the CAD drawing shown in Fig. 12. The horizontal length is 323.3 mm, while the maximum vertical length is 32.9 mm. We divided the cells at intervals of 25 mm in this CAD drawing. The velocity of the stage of the cells divided using Eq. 2 is applied as shown in Table 4. And we show the required velocity compensation for rotation/reverse rotation of cell 13 in Fig. 12. These data were calculated using Eq. 3; in Table 4, the velocity of the 13th cell is 0.45 m/s. Figure 13 is a graph showing the measurements of the signals of x and y of the scanner and those of the stage. It was found that the velocity of the compensated velocity part was higher than that of the other parts; as for the distance that the galvanometer has moved on the right coordinate, shown in Fig. 13, it can be seen that it has moved 50 mm into the scan area. This shows that in the on-the-fly system, large area processing has been successfully carried out, while not exceeding the scan area.

4 Conclusions

We have proposed a one-axis on-the-fly system in which the scanner and the stage are synchronized for laser processing of a large area. We developed a scanner board and an MOTF system for the synchronization; in order to synchronize these two systems according to the command velocity of the fabrication, we developed a stage velocity algorithm by using cell decomposition. In addition, we allowed the algorithm to compensate for the acceleration/deceleration in the rotation/reverse rotation of the stage. To prove that this on-the-fly system is even between the scan areas, we used a test that implemented low-frequency pulses to show that constant pulses appeared. And, by using these control systems and algorithm, we were able to perform marking on a large area that exceeded the scan area. At a velocity of fabrication of 100–300 mm/s, an error of approximately 60 μm was found to have occurred. Finally, through data measurements, we were able to determine that the applied algorithm and the galvanometer worked well in the scan area. It is expected that adapting the system developed in this paper will increase the quality and the velocity of the fabrication.

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