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Kerf-Taper-Angle Control and Additive Process for Formwork Laser Cutters

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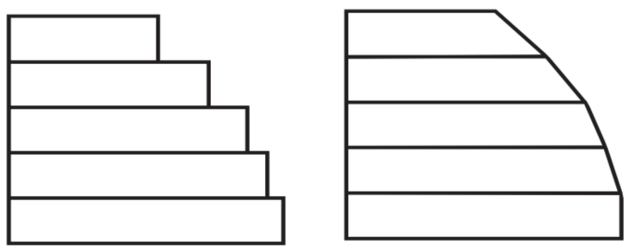
EPS (Expanded Polystyrene) formwork is used to construct freeform buildings. Freeform EPS formwork is usually made by CNC milling process, which is quite expensive. The problems of the milling process for EPS Formwork can be summarized into two factors: limitation of scale, long manufacturing time. Various studies are conducted to overcome these problems. In particular, the combination of laser cutting and additive processes can effectively solve these problems. Because laser cutting is a non-contact cutting method, it is free from the limitations of scale, and rapid production is possible through the additive process. However, when laser cutting is performed, a kerf taper angle is generated inevitably. The kerf taper angle means the cutting angle that occurs as the cut surface is formed into a trapezoidal shape by laser divergence. Due to the characteristics of the additive process using a thick plate, it has a fatal effect on the quality of the result as a sawtooth-shaped lamination trace. In this paper, a compensation technique was devised to solve this angle. It is a control the vertical angle of the tool's travel direction so that the laser diverges to the cutting waste. Path generation strategies and application of laser parameters need to be studied. In this paper, the diffusion angle of the laser passing through the lens is calculated using the laser parameters, and a corrected tool path generation strategy is established accordingly. The vector was calculated through Rodrigues rotation and applied to the 5-axis laser. Lastly, the shape that can be made may be limited due to the angular limit of the 5-axis laser. To overcome this, we propose a multi-plane additive manufacturing system. Compared the results with the existing ones to verify the performance improvement. The new construction method was applied to make a formwork, and a freeform bench model was constructed and exhibited.

1. Introduction

To build freeform concrete structures, a freeform formwork is required. These formworks have been made of iron or wood, but recently, automation and rapid production are being actively studied through formworks made of Expanded Polystyrene [1]–[4]. Such EPS formwork is generally manufactured by CNC Milling process, which raises the problem of high automation difficulty and cost. In particular, limitations of scale and long production times are pointed out as limitations of the construction method. This limitation can be effectively solved by using the lamination process [2], [5], Research on optimizing the cutting method for such lamination eps is in progress.

By utilizing the characteristic of EPS, which is very weak to heat, a cutting method using heat is usually used. Examples include hot blades, hot wires, and co2 lasers [5]–[7]. A limitation of the method using a hot blade or a hot wire is that a cutting force is applied to the workpiece because of the use of a contact cutter [8]. Because of the effect of the cutting force, a mechanism for fixing the material is required, the workpiece may be subject to bending or vibration, and there is a limit to the machinable[8], [9] size. Therefore, it can be seen that the method of placing and cutting on a honeycomb board using a laser, which is a non-contact cutter, is the most efficient in terms of cost.

In this paper, the S-LOM (Sloped-Laminated Object Manufacturing) method is used to manufacture freeform concrete formwork by applying LOM technique. First, the LOM process refers to a method of forming a sheet material coated with an adhesive by 2D cutting it according to the shape and then depositing it. Compared to processing equipment, it can produce large prints and has the advantage of low material cost.



(a) Staircase effect (b) Sloped angle

Fig. 1 S-LOM method

However, if thick EPS is used as a material for the LOM process, the Staircase effect increases[4], [10]. The Staircase effect refers to the error that occurs when the shape of the formworks that varies from layer to layer is piled up in the thickness direction. As the thickness of one-layer increases or the layered shape changes rapidly, it becomes extreme. In order to solve this error while preserving productivity, the S-LOM process adds a rotational axis to the laser machine to create a sloped angle on the sidewall of each layer.

When thick plate cutting is performed using a laser, kerf-taper-angle problems are inevitably encountered. The kerf-taper-angle refers to the cutting angle that occurs as the cut surface is formed into a trapezoidal shape by laser divergence. It has a fatal effect on the quality of the result due to the method of stacking thick plates. In this paper, a compensation technique was devised to solve this angle. Controlling the vertical angle of the 5-axis laser machining tool's travel direction to rotate so that the laser spreads toward the cutting waste. There are papers confirming this idea in the field of abrasive waterjet [11], In order to apply it to laser CNC machining tools, it is necessary to study the cutting path generation strategy and the reflection of the parameters of the laser.

A. Equipment

The equipment used in this study is an F3D Printer. This is an automatic laminating equipment composed of 5-axis CNC laser cutter, pallet changer, and palletizer. 5-aixs CNC laser cutter performs cutting with a gantry type equipment consisting of 3-axis linear motion and 2-axis rotational motion. Using 900mm*900mm EPS sheet as a material, SLOM cutting corresponding to one layer of a given shape is performed and laminated automatically. This makes it possible to produce large freeform formworks cost-effectively.

As CAD/CAM tools, Autodesk Inventor and its add-ons were used. After dividing the layer according to the size of the plate, a tool path was created using swarf as a tool creation path strategy. The generated tool path is solved by the post processor made in MATLAB to solve the inverse kinematics and machined appropriately for the machine by using the angle compensation technique. As a material, bead classification No. 1 (Korean Industrial Standard KSM3808) EPS board was used.

Fig. 2 F3D printer

B. Beam shape

Reci's 75W CO_2 Laser tube was used. The CO_2 laser has a wavelength of 10.6 μm and is a Gaussian beam that diverges in the form of a hyperbola. Due to the characteristics of the gantry-type optical equipment, the method of passing through many mirrors and irradiating the target increases the distance through which the laser passes, which inevitably causes divergence. In addition, the propagation length changes according to the y-axis movement, which causes a difference in the degree of divergence.

When laser cutting is performed, the cross section appears as a curved surface due to divergence. The same problem occurs in high-power metal cutting, but it is of low importance because a thin plate is used for general laser cutting. In the case of low power EPS laser cutting for LOM, the above effect is very large as it cuts thick plates. The problem of being expressed as if there is a fullness that is different from the actual required shape or cutting as if there is a cutting angle appears. Therefore, in order to solve this problem, this paper proposes a method to improve the precision of the output by controlling the 5-axis laser. For beam parameters, the general nomenclature presented in Siegman's Laser was used [12].

C. Angle Compensation

In order to perform cutting, there are a method of placing the beam focus in the center of the thickness direction and a method of placing it on the surface. When cutting in a way that puts the focus in the center, an error in the shape of fullness occurs in the product, or, when cutting by placing it on the surface, an error in the diagonal shape according to the depth occurs. In order to reduce the error, the cutting quality is improved by changing the direction of the laser to the byproduct direction. As a key boundary condition, the effective cutting tool diameter was set to be the same on the top and bottom surfaces. In the additive process, it is possible to reduce the cost required for the post-processing process by using these boundary conditions.

To apply this cutting method, it is necessary to distinguish which product is and which by-product is on the already generated G-code. This results in a problem of determining the inside and outside in a closed-line composed of an array of points referred to by g-CODE. When a half-straight line is drawn in an arbitrary direction, the point inside intersects the closed line odd times, and the point outside intersects even times. Using this property, we establish a formula to distinguish between inner and outer directions at any boundary existing on the G-code in the post-processing stage. First, all discrete points on the G-code are replaced with data in the form of Vector Array. we construct the normal line for a line segment consisting of any (n, n+1) point of the vector array as a parameter straight line. These intersections can be divided into three directions based on the positive, zero, and negative values of s. The zero value intersects the boundary line segment at the starting point where the normal starts, and intersects even and odd times differently in the positive and negative ranges of s. This distinguishes between the inside and the outside. Then, the improved G-code is obtained by compensating through the Rodriguez rotation formula.

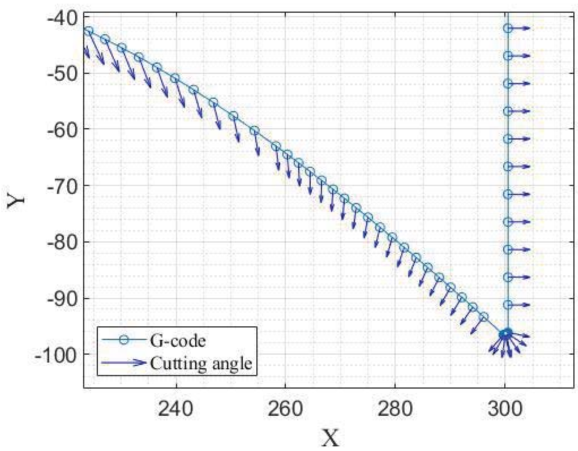


Fig. 3 Angle compensation on G-code

D. Multi-plane Additive Manufacturing System

The cutting angle limit of this machine was set at 60 degrees. As the angle of rotation increases the distance the beam passes through the material, the divergence increases, increasing the kerf width and error. Therefore, when lamination is performed in one axial direction, the shape that can be manufactured is limited. The lamination method proposed is this study is multi-plane additive manufacturing system, which is performed by changing the lamination direction according to the angle of the freeform surface. this method divides the surface of the freeform formwork into triangles to obtain normal vector of each triangle, and laminates freeform formwork in the direction of the axis with the largest value among the x, y, and z components of the normal vector of each plane. The lamination direction is determined in up to three directions by the value of normal vector. The spherical surface was partitioned according to the method. The legend indicates the axial direction in which stacking is possible.

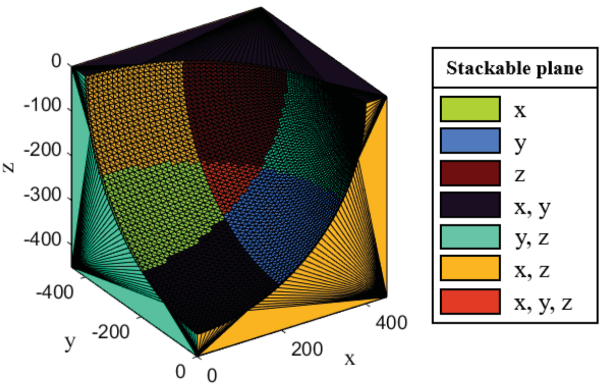
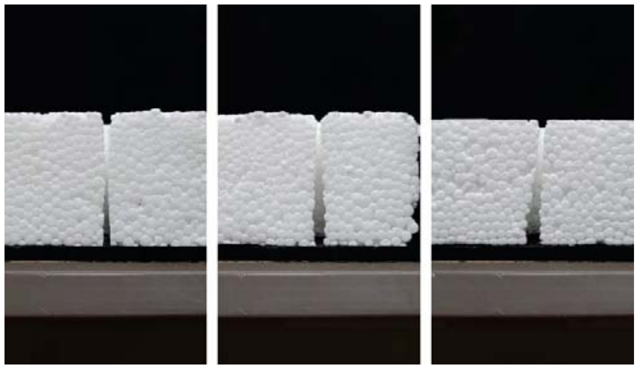


Fig. 4 Concave 1/8 sphere showing stackable plane

2. Experimental result

The error caused by beam divergence decreases as the thickness of the material decreases. However, since the thickness is directly related to the number of layers to be laminated, it is highly related to productivity. In the actual freeform, the error rate increases because the depth of the material through which the beam must pass increases according to the rotation angle. For example, a beam rotated 60 degrees must pass 40 mm to cut a 20 mm plate. Therefore, using EPS less than 20 mm has high stability. In this experiment, characteristics were considered using an EPS plate with a thickness of 30 mm. As discussed in the introduction of beam shape, the material was cut by cutting with the focus on the surface and cutting with the focus on the center, and the error generated in the material was compared. The Gaussian beam shape was estimated using the focal length of the lens and the waist spot size. Since EPS is very weak against heat, it is assumed that the estimated beam shape and the actual cutting shape are the same. Thereafter, the compensation angle was obtained through the estimated beam shape. Fig. 5 (a) shows the specimen with the focus in the center. It is difficult to control the error caused by the change of the rotation angle. Fig. 5 (b) is a specimen with focus on the surface. It can be seen that the kerf width is relatively large, and there is a recessed shape on the surface due to heat diffusion. Fig.5 (c) is a specimen to which the method is applied. It can be seen that the shape on the right has been improved.

Due to the characteristic of EPS created through bead expansion beads are dropped or empty. Because the surface is not uniform, there are difficulties in measurement. After photographing at 4032*3024 resolution, parameters were measured through pixel analysis. The pixel unit length was measured to be 0.04 mm. Beam waist w_o was measured to be 18 pixels, which is 0.72mm. The beam diameter D just before passing through the lens was measured to be 10 mm, and the focal length f of the mounted lens was 75 mm. The divergence slope of the focused beam becomes f/D. The divergence angle obtained through the slope was measured to be 3.814 degrees. Through the above values, a hyperbola expressing the beam shape was drawn, and a new effective tool diameter and compensation angle were calculated by applying the boundary condition to equalize the kerf width. The compensation angle was calculated as 3.128 degrees, and the above results are summarized in Table. 1 is shown.



(a) Center (b) Surface (c) Compensated

Fig. 5 EPS Specimens

Table. 1 Specimens analysis results

	(a)	(b)	(c)
Effective tool diameter (mm)	2.12	0.72	0.72
Cross-sectional area error (mm^2)	12.54	22.03	3.13

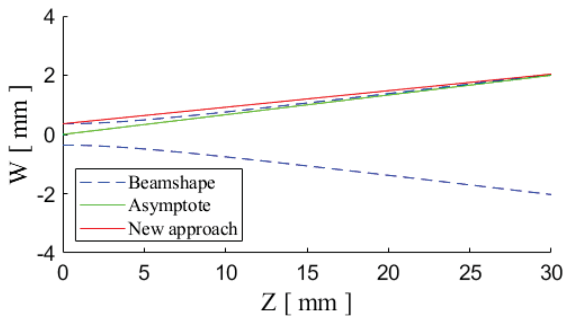


Fig. 6 Compensation angle calculation

3. Conclusions

In order to increase the precision of the S-LOM method, the compensation angle of the 5-axis laser cutter was obtained, and the values were compared. Compared to the conventional output method, the central focus method, the cross-sectional area error was reduced to 25%. The laser cutter-lamination method has remarkably high productivity compared to the existing milling method, but it has been pointed out as problems such as low precision and the need for post-treatment processing. The novel approach of this paper is expected to significantly reduce errors caused by kerf taper angles, thereby increasing precision while maintaining high productivity. In addition, to solve the problem of angle limit, which was difficult for automation, the *multi-plane additive manufacturing system* was presented. Using the method of the thesis, the test bed formwork was printed and a freeform bench model was produced and exhibited at

BEXCO, Busan. (Fig. 7)

As a future work, it is necessary to solve the limitation of the gantry type laser structure. The gantry type had a problem in that the divergence was changed as the laser passing distance increased according to the movement of the Y-axis. If fiber laser is used, it will be possible to design a laser that is mechanically more robust to environmental changes. There is no divergence problem due to axis movement, and rotation without offset is possible.

Fig. 7 Freeform bench model

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REFERENCES

[1] B. G. de Soto *et al.*, "Productivity of digital fabrication in construction: Cost and time analysis of a robotically built wall," *Automation in construction*, vol. 92, pp. 297–311, 2018.

[2] H. Ahn, D. Lee, W. Ji, W. Lee, and H. Cho, "Development of Method for Manufacturing Freeform EPS Forms Using Sloped-LOM Type 3D Printer," *Journal of the Korea Institute of Building Construction*, vol. 20, no. 2, pp. 171–181, Apr. 2020, doi: 10.5345/JKIBC.2020.20.2.171.

[3] D.-Y. Lee, D.-M. Lee, H.-H. Cho, and K.-I. Kang, "The Production Process and Mock-up Test of Freeform Concrete Segments using LOM type 3D Printer," *Journal of the Korea Institute of Building Construction*, vol. 18, no. 1, pp. 89–98, Feb. 2018, doi: 10.5345/JKIBC.2018.18.1.089.

[4] S. Jeong, J. Sim, H. Kim, D. Shin, and D. Hong, "Application of LOM for Freeform Architecture," *KSPE*, vol. 34, no. 12, pp. 903–909, Dec. 2017, doi: 10.7736/KSPE.2017.34.12.903.

[5] J. Sim, H. Kim, K. Park, C. Kim, and D. Hong, "Manufacturing Automation System of Freeform Concrete Formwork Using S-LOM Method," *KSPE*, vol. 37, no. 1, pp. 43–50, Jan. 2020, doi: 10.7736/JKSPE.019.125.

[6] A. Søndergaard *et al.*, "Robotic hot-blade cutting," in *Robotic fabrication in architecture, art and design 2016*, Springer, 2016, pp. 150–164.

[7] D.-G. Ahn, S.-H. Lee, D.-Y. Yang, B.-S. Shin, and Y.-I. Lee, "Investigation of Cutting Characteristics of Linear Hotwire Cutting System and Bonding Characteristics of Expandable Polystyrene Foam for Variable Lamination Manufacturing (VLM) Process," *Journal of the Korean Society for Precision Engineering*, vol. 17, no. 12, pp. 185–194, 2000.

[8] N. Karmakar, H. Chitikena, V. M, and S. Subbiah, "Direct Wire-Tension Measurement Based Bowing Correction in Hot Wire Cutting of Polystyrene," *Procedia Manufacturing*, vol. 48, pp. 230–236, 2020, doi: 10.1016/j.promfg.2020.05.042.

[9] D. G. Ahn, S. H. Lee, and D. Y. Yang, "Development of transfer type variable lamination manufacturing (VLM-st) process," *International Journal of Machine Tools and Manufacture*, vol. 42, no. 14, pp. 1577–1587, Nov. 2002, doi: 10.1016/S0890-6955(02)00054-8.

[10] Y. Suping, T. Murakame, and N. Nakajima, "Accuracy study on laminated object manufacturing for the metallic functional parts with complex surface," in *the Proceedings of 10th Annual Solid Freeform Fabrication Symposium, Austin of Texas, USA, Aug*, 1999, vol. 9.

[11] D. Shanmugam, J. Wang, and H. Liu, "Minimisation of kerf tapers in abrasive waterjet machining of alumina ceramics using a compensation technique," *International Journal of Machine Tools and Manufacture*, vol. 48, no. 14, pp. 1527–1534, 2008.

[12] A. E. Siegman, *Lasers*. University science books, 1986.