Rapid Fabrication of Large-sized Solid Shape using Variable Lamination Manufacturing and Multi-functional Hotwire Cutting System

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Abstract **Reviewed, accepted August 29, 2005**

Rapid prototyping (RP) technologies have been widely used to reduce the lead-time and development cost of new products. The VLM-ST process has been developed to overcome the currently developed RP technologies such as a large building time, a high building cost, an additional post-processing and a large apparatus cost. However, the VLM-ST process has the limitation of fabricated model size (VLM300: 297×210 mm, VLM400: 420×297 mm) and the limitation of slope angle when the large-sized model more than 600 × 600 × 600 mm or axisymmetric shape is fabricated. The objective of this paper is to develop a multi-functional hotwire cutting system (MHC) using EPS-foam block or sheet as the working material in order to fabricate a large-sized shape more than 600 × 600 × 600 mm. Because the MHC apparatus employs a four-axis synchronized hotwire cutter with the structure of two XY movable heads and a turn-table, it allows the easy fabrication of various 3D shapes, such as (1) an axisymmetric shape or a sweeping cross-sectioned pillar shape using the hot-strip in the form of sweeping surface and EPS foam block on the turn-table, (2) a polyhedral complex shape using the hotwire and EPS foam block on the turn-table, and (3) a ruled surface approximated freeform shape using the hotwire and EPS foam sheet. In order to examine the applicability of the developed MHC apparatus, an axisymmetric shape, a polyhedral shape and a large-sized freeform shape were fabricated by the apparatus.

Key Words : Rapid prototyping, Large-sized solid shape, VLM-ST process, MHC process, Process design, Apparatus design, Three-dimensional prototypes

Introduction

Recently the life cycle of products has become shorter and shorter in the marketplace because of various and changeable customers' demands. In addition, companies have to bring their products to the market at a price as low as possible.

Since it is almost impossible for conventional methods of product development based mainly on machining(eg. CNC, wire EDM) to meet with the requirements, research into the reduction of time and cost for product development are in full swing especially, in the fields of severe competition such as automobiles, electric home appliances, electronics, etc., in which diverse product models and frequent change in product design are indispensable.

Therefore, unlike the traditional machining-based approaches, rapid prototyping system is proposed as a new product development system that enables manufacturers to reduce the time and cost needed, especially in the prototyping stage which is one of the most costly processes of product development. Furthermore, rapid prototyping system is a manufacturing system that is very suitable for the concurrent engineering environment, so that it can surely play a major role in shortening lead-time, reducing cost, and ensuring quality improvement.

Rapid prototyping (RP) is a terminology that embraces a range of new technologies for producing physical parts directly from CAD models within relatively a short time. The principle of RP technology is successively adding raw material, layer-by-layer in 2.5D layer, to create a part in accordance with a CAD model.

In 1987, Stereolithography Apparatus (SLA), a rapid prototyping (RP) process that solidifies layers of ultraviolet (UV) light-sensitive liquid polymer using light from a laser, was first developed by 3D Systems in the USA. Since then, many thin-layered RP technologies have been commercialized, including FDM (Fused Deposition Modeling), SLS (Selective Laser Sintering), LOM (Laminated Object Manufacturing), JP5 (JP System 5), 3DP (3D Printing) and some other processes [1-4].

RP techniques, however, have unique characteristics according to their working principles: the stair-stepped surface of a part due to layer-by-layer stacking, low building speed caused by point-by-point or line-by-line solidification to build one layer, and additional post-processing to improve surface roughness. That is, the existing RP processes with thin layers and stair-stepped surfaces take a comparatively long time to manufacture large objects and leave a rough surface finish.

To overcome these disadvantages of the existing thin-layered RP processes, a few groups have developed thick-layered RP technologies, such as CAM-LEM (Computer-Aided Manufacturing of Laminated Engineering Materials), ShapeMakerⅡ, and TruSurf (True Surface System), so as to improve the building speed and the surface finish by using thicker layers and sloping surfaces.

Thomas et al. [5-7] at the University of Utah developed the ShapeMakerⅡ by employing the two plotter heads connected by a hotwire that cuts sheets of one-inch-thick polystyrene foam, which are then indexed and assembled manually, in order to fabricate large-scale objects. The proposed ShapeMakerⅡ system has several shortcomings. First, when creating a ruled surface, it is difficult to connect rapidly changing contours or contours without the same number of loops. That is, this method has a problem in determining which part of the top contour to connect with the bottom contour. Second, the hotwire cutter cannot cut a multiply-connected domain because it goes through the foam. Third, the melted area is inconsistent due to the inequality of power for the hot wire, which is induced by a change of wire tension and wire length during the rotation.

Thomas et al. also developed the latest version of the thick-layered ruled edge machine called ShapeMaker 2000. It is a four-axis waterjet cutter capable of building prototypes of 20 or more feet in size. It uses a semi-manual process that requires manual stacking and manual STL file splitting to remain within the machine's 3 ft × 5 ft cutting envelope. Hope et al. [8] developed a TruSurf system to cut the sloping layer surfaces with a five-axis waterjet cutter that match the surface contour. The cut layers are then glued together by hand. TruSurf uses polystyrene foam sheets of about 10 mm thickness for building a large object where the volume of the prototype is of the order of one cubic meter or greater because of its very low cost and ease of cutting. The CAM-LEM process [9] has been developed through a joint project between Case Western Reserve University and CAM-LEM, Inc., employing a five-axis laser cutting system that cuts polystyrene foam of about 6 mm thick. The system is composed of a laser for cutting, a five-axis cutting table platform, and a material-handling robot. If surface continuity is not guaranteed between adjacent layers in the build direction, it is difficult to create ruled surface. Another disadvantage of the CAM-LEM process is that the use of a five-axis laser cutter for a commercial system would be inappropriate due to its cost.

The above thick-layered RP research works are concentrated on fabrication of very large objects. Consequently, their RP processes employ very thick layers, expensive cutting systems such as a laser or waterjet (excluding SMII) and fully manual or extremely large automatic manipulation systems. Despite some advances in RP technology, it is still necessary to develop an effective process that overcomes the deficiencies of the current commercialized RP systems and the problems of the previous thick-layered RP studies. A new rapid prototyping process, Variable Lamination Manufacturing using polystyrene foam (VLM-ST) [10-14], has been developed to reduce building time, to decrease the stair-stepped effect of parts, to minimize the post-processing with thick layers and sloping surfaces. The VLM-ST process employs a 4-axis-controlled hotwire cutter and expandable polystyrene foam sheet as a laminating material of the part. However, the VLM-ST process has the limitation of fabricated model size (VLM300: 297×210 mm, VLM400: 420×297 mm) and the limitation of slope angle when large-sized model more than 600 × 600 × 600 mm or axisymmetric shape is fabricated.

In this paper, a multi-functional hotwire cutting process (MHC) using EPS-foam block or sheet as the working material is proposed in order to fabricate a large-sized shape more than 600 × 600 × 600 mm. Because the MHC apparatus employs a four-axis synchronized hotwire cutter with the structure of two XY movable heads and a turn-table, it allows the easy fabrication of various large-sized model, such as (1) an axisymmetric shape or a sweeping cross-sectioned pillar shape using the hot-strip in the form of sweeping surface and EPS foam block on the turn-table, (2) a polyhedral complex shape using the hotwire and EPS foam block on the turn-table, and (3) a ruled surface approximated freeform shape using the hotwire and EPS foam sheet. In order to examine the applicability of the developed MHC apparatus, an axisymmetric shape and a polyhedral shape are fabricated by the apparatus. In addition, miniature of the admiral Yi Sun-Sin with the envelope model dimensions of 630 × 440 × 1315 mm has been fabricated using the semi-automatic VLM-ST process and the MHC process in connection with the reverse engineering technology.

Description of the Multi-functional Hotwire Cutting process

In the MHC process, EPS foam sheet with the size of 1200 × 900 mm using a four-axis synchronized hotwire cutter with the structure of two XY movable heads is cut in accordance with CAD data. The shaped EPS foam sheet is laminated to fabricate the large-sized model. In addition, an axisymmetric shape and a polyhedral shape, which are difficult in the VLM-ST process, can easily be fabricated using EPS foam block, turn-table, and the curved hot-strip.

The MHC apparatus comprises a four-axis synchronized hotwire cutter with the structure of two XY movable heads, turn-table and control software as shown in Fig.1. Table 1 shows the specifications of the MHC apparatus.

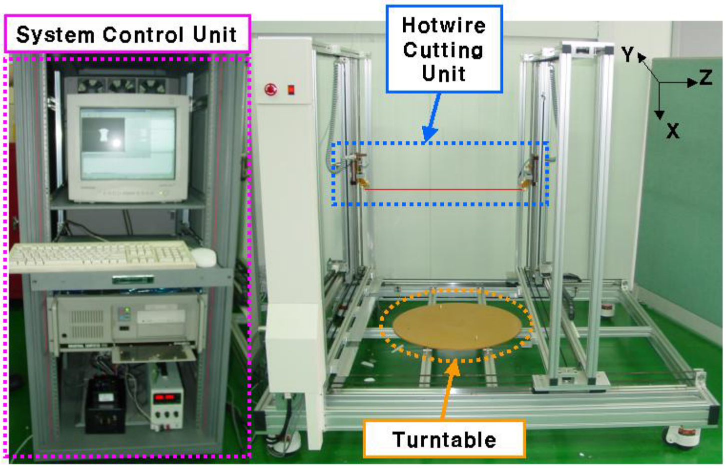

Fig. 1 Multi-functional hotwire cutting apparatus

Table 1 Specifications of multi-functional hotwire cutting system

Material	EPS-foam block EPS-foam sheet (1,200 x 900 x 20 mm)
Cutting system	4-axis synchronized hotwire cutter with the structure of two XY movable heads
Cutting speed	50 mm/sec (Maximum)
Control	PC-NC

The MHC process has three characteristics: (a) the vertical feeding system of material, (b) the control system of hotwire tension, and (c) cutting EPS foam block with the turn-table and the curved hot-strip.

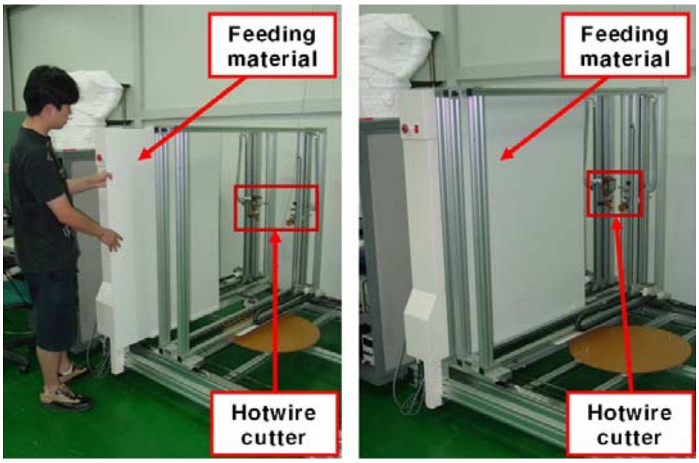

Fig. 2 Vertically supplied material

In order to minimize the deflection generated by gravity, the material is vertically fed into MHC system as shown in Fig. 2. Because the deflection increases at cutting when the large size of material is horizontally fed, the vertical feeding system of material is chosen. Fig. 3 shows the hotwire tension control unit in the MHC apparatus composed of rotating magnetic disk and steel disk. In RP process like ShapeMaker II, the melted area is inconsistent due to inequality of power for the hot wire, which is induced by a change of wire tension and wire length during the rotation. In order to overcome these limitations, the MHC machine employs the hotwire tension control unit. The control unit works as follows: when the hot wire is loosened, the combined magnetic disk and steel disk winding the hotwire rotates to increase the wire tension. When the hotwire tension is equal to the magnetic force, the steel disk separated from the magnetic disk is not rotated to maintain wire tension.

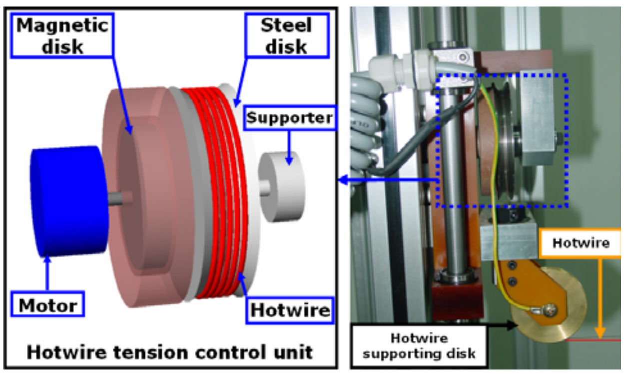

Fig. 3 Hotwire tension control unit

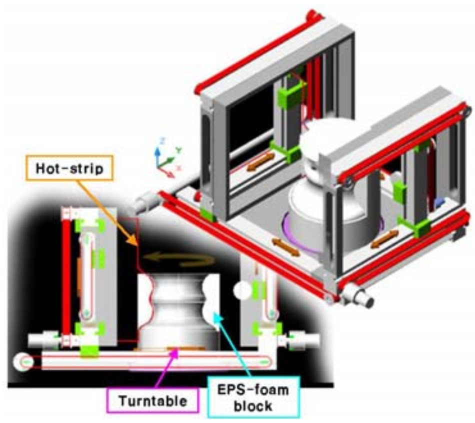

Fig. 4 Hot-strip and turn-table

An axisymmetric shape and a polyhedral shape, which are difficult in the VLM-ST process, can easily be fabricated using EPS foam block, turn-table, and the curved hot-strip as shown in Fig.4. The hot-strip is curved manually in according to sketch of cross-section shape. After the curved hot-strip and EPS foam block are set up on the turn-table, the hot-strip goes through EPS foam block while the turn-table is rotating. A polyhedral shape can also be fabricated when the hotwire cuts the EPS foam block at a given angle using the turn-table.

Generation of MHC data in CAD/CAM software

Though previous thick-layered RP researchers have proposed their methods to produce thick layers with angled edges from the CAD model for the purpose of improving building speed and surface finish, they still have problems such as the determination of which part of the top contour to connect with the bottom contour and the generation of a discontinuous saw-toothed shape at the layer boundaries. Because of the use of thick layers and sloping edges with the first-order approximation between layers, the MHC process requires a new method to generate cutting path data suitable for the devised two plotter heads connected by the hotwire in order to create 3D layers. The CAD/CAM system for MHC system, which is named the MHC-Slicer, is software to automatically generate 3D toolpath data from the STL data. The MHC data are the final output data, which are imparted to MHC apparatus. Fig. 5 shows the procedure to generate the cutting path data of the linear hotwire cutter for the MHC process. The MHC apparatus is divided into the CAD process to produce the mid-slice from the STL file and the CAM process to produce the cutting path data from the mid-slice. The MHC-Slicer integrates these CAD and CAM processes.

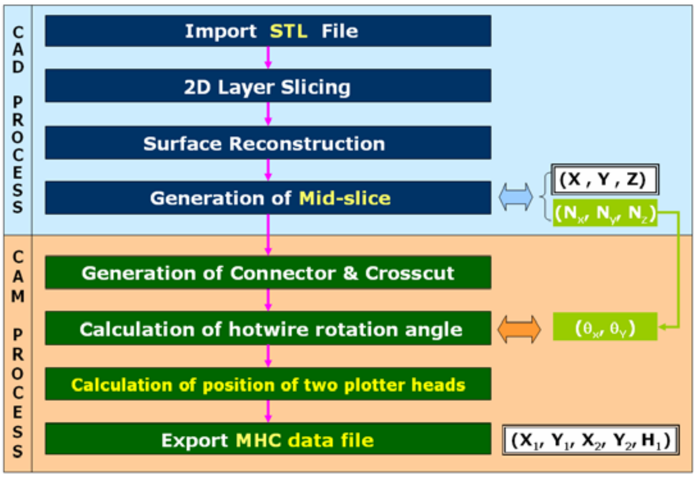

Fig. 5 Procedure of MHC-Slicer

Description of hotwire cutter posture

The position of each plotter head can be calculated from the obtained hotwire rotation angles. The posture of hotwire cutter and plotter head is illustrated in Fig. 6. W is the distance of Z-direction between the axes of hotwire supporters. R is the radius of hotwire supporting disks. C is the perpendicular distance of Z-direction between the axis of hotwire supporter and the axis of hotwire supporting disk. W, R, and C are the parameters to determine the position of each plotter head.

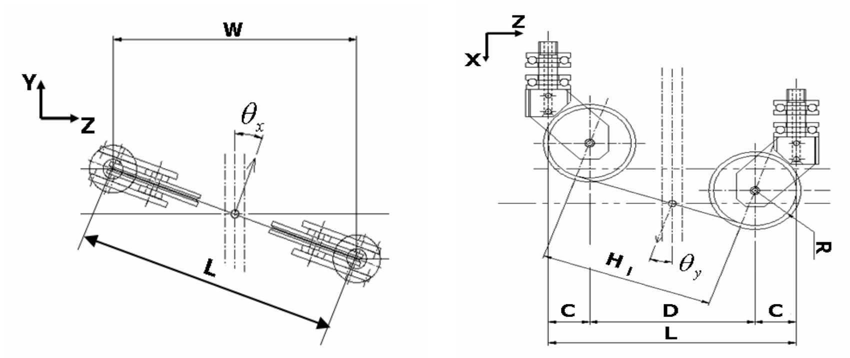

Fig. 6 Posture of hotwire cutter

Calculation of plotter head positions

USL(Unit Shape Layer) data including the hotwire rotation angles of each vertex (x, y, θ_x, θ_y) are used to calculate two plotter head positions. L, D, and Φ are calculated using parameters W, C as follows.

$$L = \frac{W}{\cos\theta_x} \quad (1)$$

$$D = L - 2 \cdot C \quad (2)$$

$$\phi = \tan^{-1}(\tan\theta_y \cdot \cos\theta_x) \quad (3)$$

where L is the perpendicular distance between the axes of hotwire supporters, D is the perpendicular distance between the axes of hotwire supporting disks, Φ is the angle between hotwire and Z-direction vector.

Hence, two plotter head positions (X_1, Y_1, X_2, Y_2, H_l) using the rotating angle of USL data, the calculated D and Φ are given by the expression.

$$X_1 = x - [D/2 \cdot \tan\phi + R(1/\cos\phi - 1)] \quad (4)$$

$$Y_1 = y + W/2 \cdot \tan\theta_x \quad (5)$$

$$X_2 = x + [D/2 \cdot \tan\phi - R(1/\cos\phi - 1)] \quad (6)$$

$$Y_2 = y - W/2 \cdot \tan\theta_x \quad (7)$$

$$H_l = D/\cos\phi \quad (8)$$

where (X_1, Y_1) are the coordinates of axes of the left side hotwire supporting disk, (X_2, Y_2) are the coordinates of axes of the right side hotwire supporting disk, H_1 is the length of hotwire.

The MHC-Slicer for the MHC process has been implemented in C++ and Visual C++ 6.0 programming language in a Windows environment. In addition, the MHC-Slicer employs the OpenGL graphics for fast display and manipulations of STL, MCG (Mid-Contour Generation), USL, and MHC data. The values of parameters W, R, C through dialog box are inputted into MHC-Slicer.

Fabrication of three-dimensional parts

In this section, in order to examine the applicability of the developed MHC apparatus, an axisymmetric shape, a polyhedral shape and a large-sized freeform shape are fabricated by the apparatus.

Axisymmetric shape

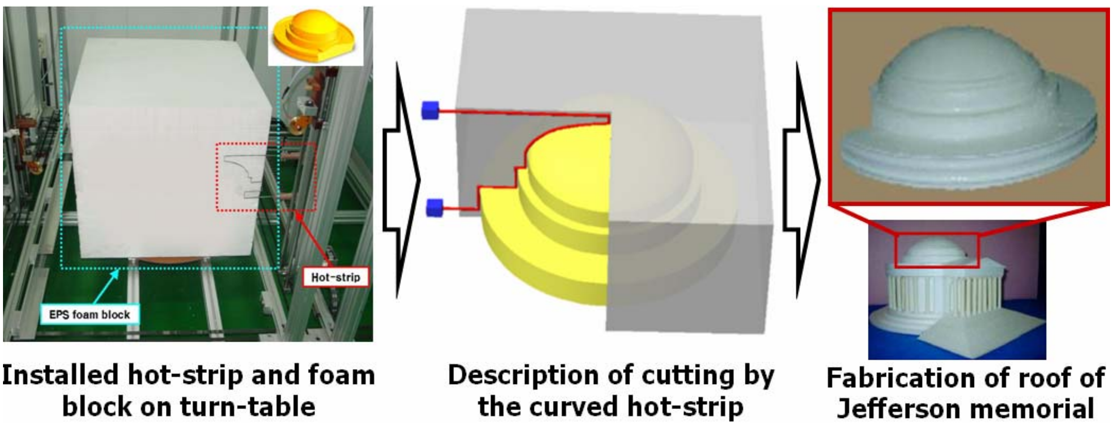

Fig. 7 Procedure for fabrication of axisymmetric shape by the MHC apparatus

The procedure to fabricate an axisymmetric shape in the MHC apparatus is as follows.

(1) The hot-strip is curved manually in according to sketch of cross-section shape.
(2) The curved hot-strip and EPS foam block which is larger than the part are installed.
(3) The heated hot-strip goes through EPS foam block while the turn-table is rotating.

Fig. 7 shows the roof of Jefferson memorial fabricated by the MHC apparatus. In case of fabricating an axisymmetric shape such as the roof shape in the VLM-ST process, the surface quality of part is quite low. However, in the MHC apparatus, an axisymmetric shape as roof of the Jefferson memorial can easily be fabricated with a good surface quality. Furthermore, the fabrication time of the MHC apparatus can be remarkably shorter than that of the VLM-ST apparatus if more than 1 m high is fabricated.

Polyhedral shape

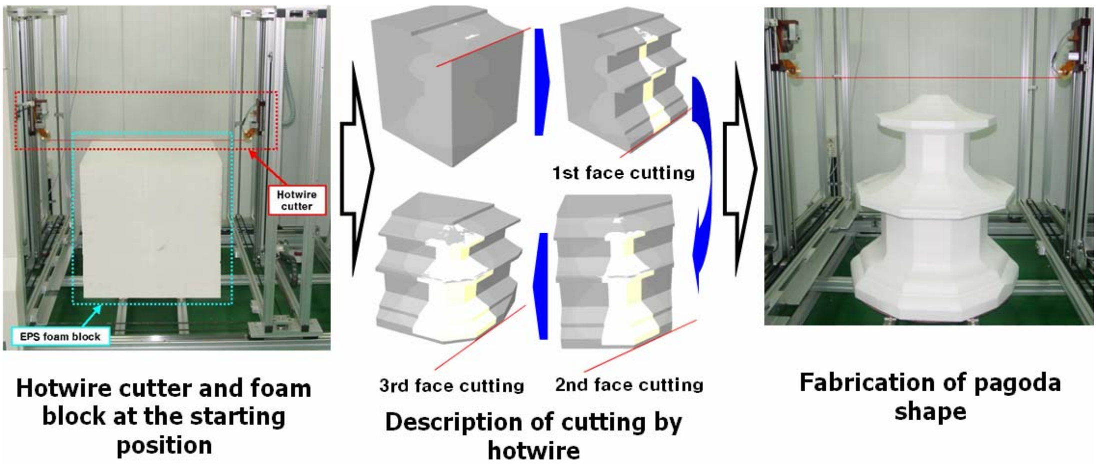

Fig. 8 Procedure for fabrication of polyhedral shape by the MHC apparatus

The procedure to fabricate a polyhedral shape in the MHC apparatus is as follows.

(1) The hotwire cutter is placed at the starting position.

(2) The EPS foam block fixed on the turn-table is rotated at a given angle.

(3) The hotwire cutter moves according to the cutting path.

Fig. 8 shows a pagoda shape with a polyhedral shape fabricated by the MHC apparatus. In case of fabricating the polyhedral shape using the VLM-ST process, the layer with the slope angle approaching closely zero degree can not be produced due to the limitation of the slope angle. However, because there is no limitation of the slope angle, a polyhedral shape as pagoda shape can easily be fabricated by the MHC apparatus.

Large-sized freeform shape

The MHC process can fabricate the large-sized part with freeform shape using laminating technology. The procedure of fabrication of the large-sized freeform shape in the MHC apparatus is as follows.

(1) STL file is generated from the scanned data or CAD model.

(2) The cutting path which is obtained from three-dimensional model is generated using the

MHC-Slicer.

(3) EPS foam sheet with a given thickness is inserted into hotwire cutting system vertically.

(4) EPS foam sheet in according to MHC data is laminated sequentially.

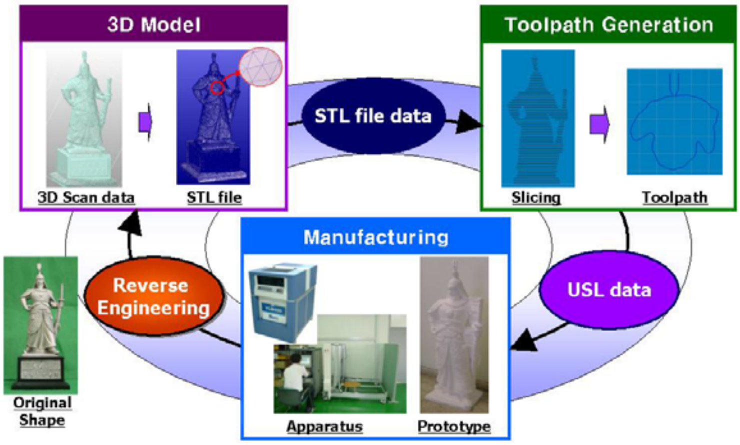

Fig. 9 Procedure for fabrication of freeform shape by the MHC apparatus: statue of the Admiral Yi Sun-Sin

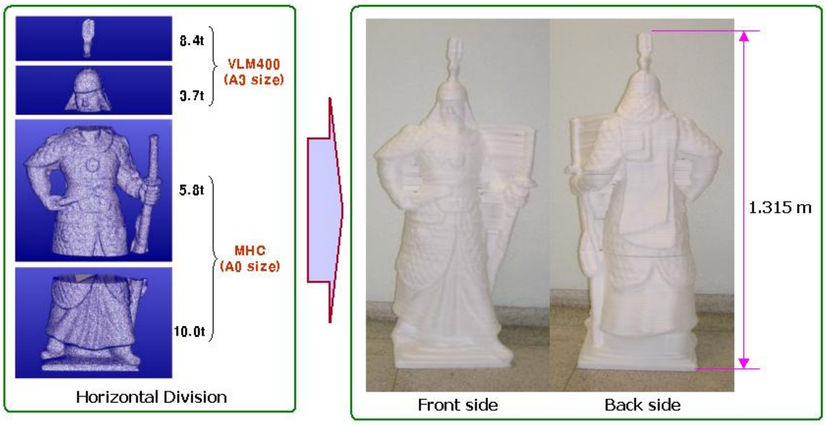

Fig. 10 Horizontal division of statue of Admiral Yi Sun-Sin considering build size and shape accuracy

As illustrated in Fig. 9, the miniature of the admiral Yi Sun-Sin with the envelope model dimensions of 630 × 440 × 1315 mm is fabricated using the semi-automatic VLM-ST process and the MHC system. In case of fabricating the large-sized part using only the VLM-ST process, the model should be divided into a large amount of sections due to the limitation of the material size (297 × 420 mm). Each section fabricated by the VLM-ST process is assembled to complete the whole part. Because of the repeated separation and assembly processes, more fabrication time is required and the dimensional error is also accumulated.

However, in case of the MHC process, the separation and assembly processes are not required to fabricate the part more than 600 × 600 × 600 mm because the MHC apparatus can cut 820 × 1060 mm EPS foam sheet as a maximum size.

In order to reduce the cutting time and save the material cost, the horizontal division of the model considering build size and shape accuracy is carried out. The head sections which are less than the size of 297 × 420 mm are fabricated using VLM400 apparatus. The body sections which are more than the size of 297 × 420 mm are fabricated using the MHC apparatus. Table 2 shows the conditions, material cost and cutting time for fabrication of the miniature.

Table 2 Fabrication specifications of statue of Admiral Yi Sun-Sin

	VLM400 (A3 size)		MHC (A0 size)	
No. of subparts	2 pieces		2 pieces	
Layer thickness	8.4 mm	3.7 mm	5.8 mm	10.0 mm
No. of layers	19 layers	47 layers	97 layers	42 layers
Material cost	₩19,000	₩28,200	₩291,000	₩168,000
Cutting speed	40 mm/sec		15 mm/sec	
Net cutting time	77 min or 1.28 hr		580 min or 9.67 hr	

Conclusions

In this work, a multi-functional hotwire cutting process (MHC) that can easily fabricate an axisymmetric shape, a polyhedral shape and a large-sized shape has been developed. The MHC process employs the turn-table and the curved hot-strip to produce an axisymmetric shape with a good surface quality. In addition, the large-sized freeform shape can be fabricated using laminating technology. When the freeform shape is fabricated, the position (X_1, Y_1, X_2, Y_2, H_l) of two plotter heads supporting the hotwire cutter is calculated by the MHC-Slicer. EPS foam sheet which is vertically inserted into the hotwire cutter system is cut according to MHC data. The shaped EPS foam sheet with the slope side is laminated manually.

In order to examine the applicability of the developed MHC apparatus, the Jefferson memorial as an axisymmetric shape, a pagoda shape as a polyhedral shape, and the miniature of the admiral Yi Sun-Sin as the large-sized freeform shape are fabricated by the apparatus. The miniature of the admiral Yi Sun-Sin with the envelope model dimensions of 630 × 440 × 1315 mm has been fabricated using the semi-automatic VLM-ST process and the MHC process in connection with reverse engineering technology.

In the future, the MHC apparatus which can manufacture large-sized freeform shape from CAD data efficiently will be applied to the field of architecture, industrial design, advertisement, miniature for movie and so on.

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