ABSTRACT
Design is important in the IT, digital appliance, and auto industries. Aesthetic and artistic images have been applied for better quality of products. 2.5D engraving of glass products is important to fabricate aesthetic patterns in the jewelry industry. Grinding, laser and chemical methods have been used to fabricate jewelry. However, to improve productivity and quality of 2.5D machining on the glass, micro engraving through micro end-milling is required. In this paper, to improve productivity and quality of 2.5D machining on the glass, 2.5D engraving method has been developed through the ABT (Automatic Boundary Tracking) algorithm and glass machining technique. In addition, to obtain optimum cutting conditions in high-speed glass machining, Taguchi method is applied. Using the previously developed ABT algorithm and NURBS modeling [1], construction of embossed CAD data from any kinds of artistic pictures or images has been achieved. Combining the previously developed CAD/CAM technique based on the ABT algorithm with the high-speed crack-free end-milling technique, precision micro-engraving of glass has been performed. Performance of the developed system is verified through case studies.

KEYWORDS: 2.5D engraving, ABT, Aesthetic pattern, Glass machining, Micro end-milling.

INTRODUCTION
Recently, design is important for upgrading quality of products and manufacturing high value-added goods. Using the aesthetic and artistic design patterns, design quality of commercial products is significantly upgraded. This generates TechArt technology in the IT, digital appliance, and auto industries. TechArt means a design technology to transform engineering items to products with aesthetic design features. Using the artistic design patterns, design quality of commercial products is significantly upgraded. Valuation of jewelry, IT, digital appliance and auto products is improved as well [1,2].

2.5D engraving of glass products is important to fabricate aesthetic patterns in the jewelry industry. Grinding, laser and chemical machining methods have been used to fabricate jewelry. However, heat affection, chemical damage and lack of the 2.5D engraving system have limited the engraving application so far. To fabricate a small and complex aesthetic pattern on the jewelry, precision glass engraving technique through crack-free machining is required. As the glass is brittle material, cracks are generated due to impact load of milling. To increase machining performance, high-speed micro end-milling with critical depth of cut is required for the development of crack-free micro engraving process. In this paper, to obtain optimum cutting conditions in the high-speed glass machining, Taguchi method is applied. Using the previously developed ABT algorithm and NURBS modeling [1], construction of embossed CAD data from any kinds of artistic pictures or images has been achieved. Combining the previously developed CAD/CAM technique based on the ABT algorithm with the high-speed crack-free end-milling technique, precision micro-engraving of glass has been performed. Performance of the developed system is verified through case studies.

2.5D ENGRAVING METHOD
Images are contaminated by noise. It deteriorates quality of reconstructed 2.5D CAD models. To reduce the noise, color images are transformed to gray images first. To remove impulse and salt-and-paper noises without blurring of the image, an adaptive median filter [1,2] is applied to the image. Then binary image is obtained through multiple threshold according to designer’s intention. In the application of the adaptive median filter, selection of the proper window size is important to enhance clearness of the image [2].

To get 2.5D solid CAD models from an image, edge information should be extracted from the image first. The ABT is used to get boundary curves from point loops, as well as real loops composed of closed curves or closed twist curves in a 2D image [1]. Fig. 1(a) shows a 2D image. Fig. 1(b) shows extracted boundary curves through the ABT algorithm. It is
confirmed that the devised ABT algorithm works well to extract closed boundary curves of aesthetic images.

FIGURE 1. (A) 2D IMAGE, (B) EXTRACTED BOUNDARY CURVES BY ABT ALGORITHM.

Secondly, to make 2.5D CAD models from pixels of the boundary curves, NURBS curve fitting of them is required. Using the chord length and average knot value methods, control points matrix for the fitting is obtained. Then, the NURBS curve of the boundary curve is obtained as

\[
P(u) = \frac{\sum_{i=0}^{n} w_i P_i N_{i,k}(u)}{\sum_{i=0}^{n} w_i N_{i,k}(u)}
\]

(1)

where \( P_i \) is the \( i \)th control points, \( w_i \) is the weight of \( P_i \), and \( N_{i,k}(u) \) are blending functions given by

\[
N_{i,k}(u) = \begin{cases} 
1 & t_i \leq u < t_{i+1} \\
0 & \text{otherwise}
\end{cases}
\]

and

\[
N_{i,k}(u) = \frac{u - t_i}{t_{i,k} - t_i} N_{i,k-1}(u) + \frac{t_{i+k} - u}{t_{i+k} - t_{i+1}} N_{i+1,k-1}(u)
\]

(2)

where \( t_i \) is the \( i \)th knot value. To secure continuity of the NURBS curve, order \( k \) is selected 3 in this paper.

To visualize and manipulate the CAD model on the commercial CAD/CAM system, IGES file conversion is used [3,4] and then endmill simulation has been performed through the solid model as shown in Fig. 2.

FIGURE 2. MACHINING SIMULATION ON POWERMILL.

TABLE 1. PROPERTIES OF GLASS.

<table>
<thead>
<tr>
<th>Material</th>
<th>Soda-lime Glass</th>
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<tbody>
<tr>
<td>Size</td>
<td>21x25x1 (mm)</td>
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<tr>
<td>Density</td>
<td>2490 (kg/m³)</td>
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<tr>
<td>Young's modulus</td>
<td>69 (Gpa)</td>
</tr>
<tr>
<td>Poisson's ratio</td>
<td>0.22</td>
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</table>

FIGURE 3. EXPERIMENTAL SETUP.
EXPERIMENTS

Soda-lime glass with property shown in Table 1 is applied for glass machining. Brittle fracture occurs during ball end-milling on the glass. Vertical and horizontal cracks are generated due to thrust and axial loads. To remove cracks in cutting, chip thickness should be controlled less than the critical thickness [5,6]. And to reduce thermal damage during cutting, machining speed achievable by the spindle speed is selected as high as possible. Fig. 3 shows the overall experimental set up installed on the high-precision CNC milling machine. TiAlN coated 2 flutes Φ0.3mm ball end-mill attached to the air-spindle with 150,000rpm spindle speed is used for experiments. This is actuated by 0.5 Mpa air pressure (HTS-1501; Nakashini Inc.).

Preliminary experiments were conducted to derive proper range of feed, axial depth of cut and rotational speed. Table 2 shows \( L_9(3^4) \) orthogonal array for crack-free ball end-milling of glass in Taguchi experiments.

<table>
<thead>
<tr>
<th>Table 2. ( L_9(3^4) ) Orthogonal Array.</th>
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<tbody>
<tr>
<td>Spindle speed (rpm), ( S_i )</td>
</tr>
<tr>
<td>1</td>
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<tr>
<td>2</td>
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<tr>
<td>3</td>
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</table>

Table 3 shows experimental results according to Table 2. Crack size, averaged crack size and \( S/N \) ratio are obtained. Averaged \( S/N \) ratios according to each process parameter are shown in Fig. 4. Spindle speed 150,000rpm, feed rate 3mm/min and axial depth of cut 0.06 mm has been selected for optimal parameters.

The objective of process optimization is to determine optimal process parameters and to reduce variation of product quality. Taguchi methods use signal-to-noise (S/N) ratio to quantify experimental variation [5,6]. In this paper, ‘smaller-the-better’ (SB) \( S/N \) ratio given by Eq. (1) is applied for reducing crack size.

\[
S/N = -10 \log \left( \frac{1}{n} \sum_{i=1}^{n} y_i^2 \right)
\]

where \( n \) represents number of repetition of a test, and \( y_i \) is measured crack size.

Table 3 shows experimental crack size and \( S/N \) ratio.

To verify performance of the developed 2.5D glass embossing system, reconstruction of CAD models, tool-path generation and micro end-milling of glass have been conducted as follows. Applying the devised ABT algorithm and the NURBS interpolation method to the image of Fig.
1, a CAD model has been obtained. To visualize and manipulate the CAD model on commercial CAD/CAM systems, it is converted to IGES files [3,4]. After constructing the 2.5D solid CAD model with 0.2mm embossment on CATIA, micro ball end-milling simulation on PowerMill is performed as shown in Fig. 2. Through G-codes obtained from PowerMill and optimal micro end-milling conditions obtained from Taguchi experiment, glass machining is conducted as shown in Fig. 5. 2.5D micro-engraving result shown in Fig. 6 is obtained from the machine vision measurement [6]. There is no crack. This confirms 2.5D micro-engraving through the developed ABT algorithm and Taguchi method on the glass is conducted well.

CONCLUSIONS
A precise 2.5D micro-engraving of glass by automatic boundary tracking (ABT) for product design has been devised. Following conclusions have been obtained:
1. Developed ABT technique including median filtering, multiple threshold and binary conversion of images extract boundary curves from any pictures well.
2. Solid models of the obtained boundary curves are obtained well through the NURBS interpolation with the chord length and average knot value methods.
3. IGES interface enables generation of G-codes on the commercial CAD/CAM system. Two flutes Φ0.3mm ball end-mill with 150,000rpm spindle speed, feed rate 3mm/min and axial depth of cut 0.06 mm has been selected for crack free micro-end milling of soda-lime glass.
4. Quality and performance of the developed system is confirmed through experiments.

REFERENCES