Multi-axis Milling for Micro-texturing

Yoshikazu Kobayashi[1,#] and Kenji Shirai[1]

1 College of Engineering, Nihon University, Fukushima, Japan
Corresponding Author /E-mail: koba@ushiwaka.ce.nihon-u.ac.jp, TEL: +81-24-956-8824, FAX: +81-24-956-8863

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The surface texture of a product is generally produced by etching or sandblasting. However, these techniques have problems related to repeatability and environmental pollution. Since current milling machines can produce small parts at the micrometer or nanometer level, the resolution of milling exceeds the manufactured dimensions of the surface texture produced by etching or sand-blasting. A method for generating surface texture by milling is proposed and demonstrated. The proposed method was demonstrated by actual milling using a three- or five-axis control machine, and the machined surface texture was measured with an interferometer to allow comparison with the designed shape. The measurement results demonstrate that the proposed method can generate a wide-area surface texture with good machining repeatability.

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1. Introduction

Surface texture is an important aspect in enhancing the aesthetic and tactile qualities of products as well as their mechanical properties. Surface texture is generated over a wide area to produce various characteristics such as patterns of tiles, annular rings, or skin. A rough texture on a product surface is generally obtained by etching or sandblasting, which produces a roughness of several hundred micrometers. However, these techniques have issues related to repeatability and environmental pollution. They also require expert control such as masking of the product surface. As well, automation of the process is difficult.

Since current high-precision milling machines can machine products at the nanometer level, the resolution of machining exceeds that achieved by etching or sandblasting. This indicates that machining could be used to generate surface texture. However, patterns produced by such high-precision machines consist of only simple shapes like lines; it is difficult to produce the complex patterns required for surface textures. Therefore, computer graphics (CG) systems that are capable of designing surface textures and mapping geometrical surfaces cannot be used in production. Computer-aided manufacturing (CAM) systems are not optimized for complex micro-fabrication applications such as the generation of a tool path. To address these shortcomings, we developed a surface texture generation system and used it to produce machined samples.

2. Concept of micro-texturing by machining

Surface textures contain micro-shapes that cover a wide area. The generation of a micro-shapes over a wide area has been studied using CG texture synthesis methods.[1,2] However, applying the huge amount of data generated from a texture synthesis to a machined surface is inefficient means of generating cutter location (CL) data.

Figure 1 shows the concept of generating surface textures. First the

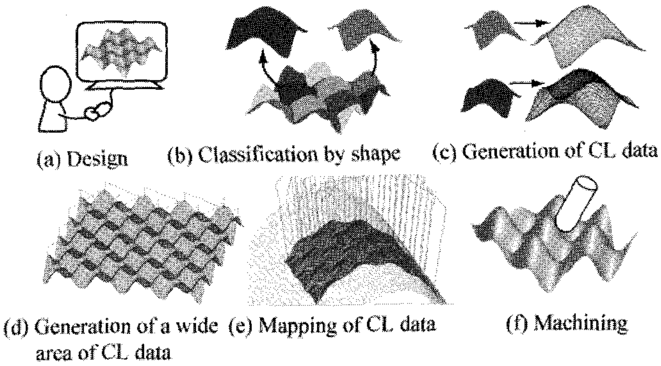


Fig. 1 Proposed procedure to machine surface texture

designer creates a microscopic surface texture, which is a pattern that can be produced using CG software or arithmetic equations (see Fig. 1(a)). Next, the designed texture is classified according to similar shapes (see Fig. 1(b)) using a classification algorithm developed from a topology theorem. The CL data are then generated to create similar shapes (see Fig. 1(c)). We considered the following conditions when generating the CL data.

1) The CL was assumed to be a spiral centered on the highest position (peak).
2) A ball end cutter was used, the radius of which was based on the surface radius of the texture.
3) The tool position and vector of the tool axis were calculated so that the tool moved smoothly.

The CL data of each similar shape are obtained by the same process while the CL surface texture data over a wide area are generated by joining and mapping the CL shape data (see Figs. 1(d) and 1(e)). Finally, the surface texture over a wide area is machined by milling using the CL data (see Fig. 1(f)).

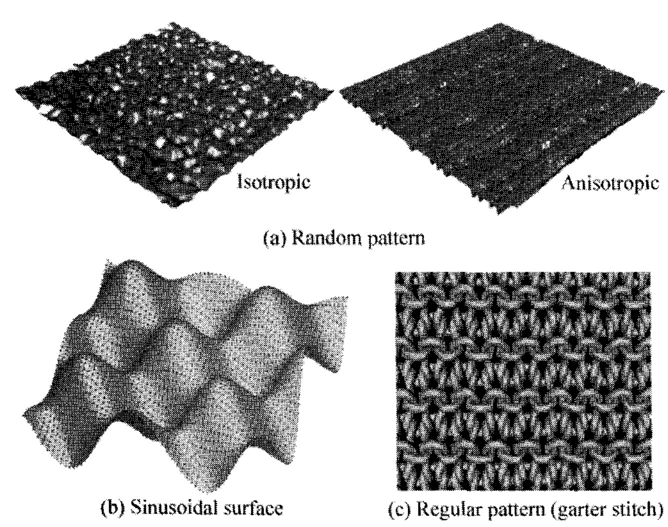


Fig. 2 Texture images designed using the new CAD system

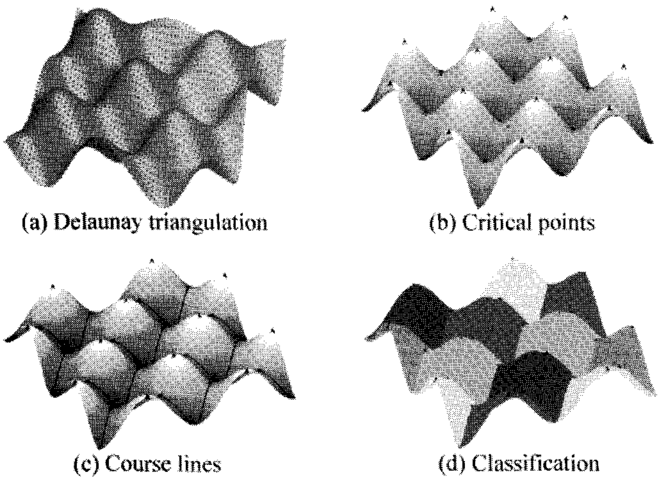


Fig. 3 Flow of classification

3. Surface texture design

It is difficult to design surface textures using commercial computer-aided design (CAD) systems, which use geometrical shapes. The CAD system we developed can design random textures such as human skin patterns and regular textures such as fabric or knitwear patterns. The algorithm for designing the random texture pattern is based on the arithmetic theory of two-dimensional (2D) auto-regressive models.[3] To design a random texture, the user inputs the values of six parameters related to the surface topography: the correlation lengths of the X- and Y-directions, the multiplier of the auto-correlation function, the root mean square, the skew, and the kurtosis. The generated random texture satisfies the statistical information defined by the six parameters. The user can also interactively redesign the random texture pictured on the screen by changing the parameters or by using certain commands.

Regular patterns are generated by either arithmetic operations or hand drawing. Arithmetic operations create continuous patterns from equations entered in the CAD system. A new algorithm was developed to generate a regular pattern by hand drawing. This algorithm was based on the L-system described by Lindenmayer[4], which is a theory of shape pattern recognition and self-assembly. Figure 2 contains examples of texture images designed on our CAD system. Figure 2(a) shows random patterns generated using 2D auto-regressive models with six parameters. Figure 2(b) was generated by the arithmetic equation of a sinusoidal surface. Figure 2(c) shows a garter stitch knitwear pattern, generated by a self-assembly algorithm based on hand drawing.

Random texture patterns are difficult to expand to a wide area because it is impossible to extract the same patterns on the designed surface texture and significant computing resources are required. Therefore, we describe only the generation of regular patterns.

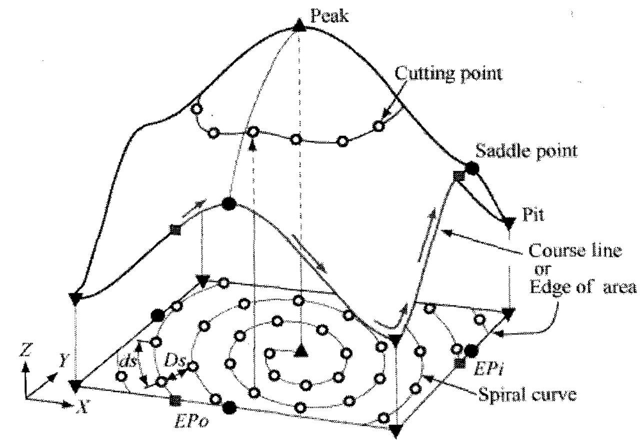


Fig. 4 Generation of the tool path on a hill

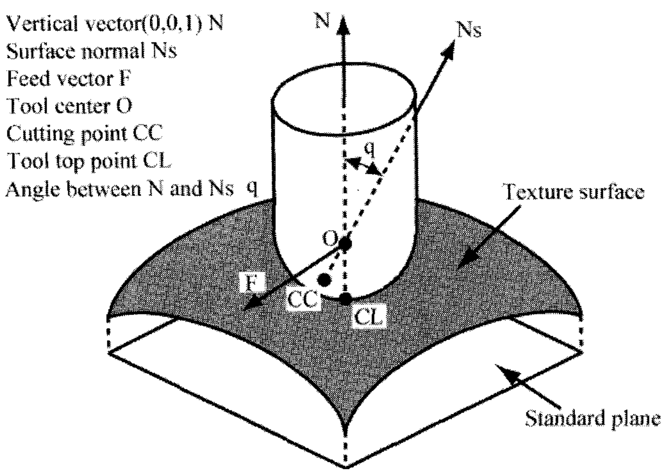


Fig. 5 Tool orientation

4. Generation of CL data

4.1 Classification of shapes on the surface texture

Similar shapes on the texture must be found to generate the CL data, as shown in Fig. 1. An algorithm based on topological features was applied for shape classification. The process used to classify the shapes is shown in Fig. 3. First, a texture pattern was designed as described in Section 3, and the resulting data were converted to have the same sampling intervals on the X- and Y-axes. The texture surface composed of lattice data was constructed by Delaunay triangulation to obtain the connection data between sampling points. In this process, the texture data were converted into STL format, which describes a triangulated surface and is supported by several 3D CAD/CAM applications. Next, the critical points, peaks, pits, and saddle points were calculated from the connection data and STL surface data.[5] A peak was defined as the highest point in its neighborhood, and, conversely, a pit was defined as the lowest point in its neighborhood. A saddle point was defined as a point dividing two or more neighboring higher areas. A course line was defined as a line connecting the points from the saddle point to the pit point with the maximum slope. Finally, a texture was classified as a set of hills enclosed by course lines or data boundaries.

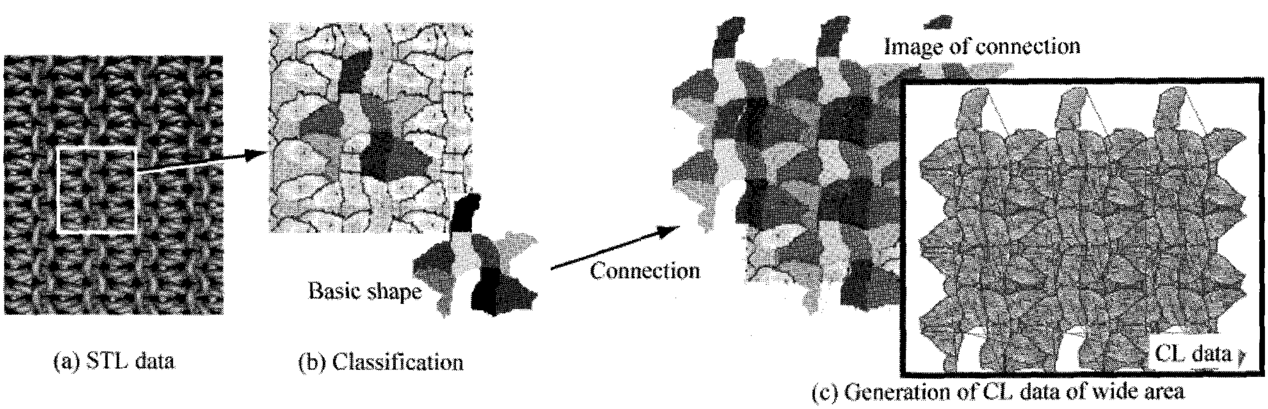


Fig. 6 Generation image of CL data of wide area

4.2 Generation of CL data with similar shapes

CL data were calculated for hills that have similar shapes, as classified by the technique described in the previous subsection. The CL data on the texture surface were generated as a spiral curve on a plane surface defined by an Archimedes' spiral with two parameters, the spiral distance *Ds*, and data distance *ds*, as shown in Fig. 4. These data were transcribed to the surface texture as cutting points. If a spiral curve crosses a course line or the outline of the data area, the cutting points for that part follow the surface data of the course line or the outline between the exit point, *EPo*, and the entrance point, *EPi*.

The machining was performed using a ball end cutter with a radius determined by the principal curvature of the texture surface. Therefore, the curvature for an arbitrary point on the surface texture was required to estimate the radius of the ball end cutter. The principal curvature for an arbitrary data point on a surface constructed by triangle meshes was obtained from [6]. Although the curvature could be calculated at all data points of the surface texture using this method, we actually calculated it at the saddle and pit points where the curvature was expected to be large.

The texture was machined based on following assumptions about the tool axes.

1) The textured surface on the plane was generated by three-axis machining.
2) The textured surface mapped on the geometrical surface was generated by five-axis machining.[7]

These assumptions were necessary to prevent extreme changes of the surface normal to the texture surface. There are many cases where the tool axis cannot be applied based on the surface normal to the rotation table of a five-axis machine, *e.g.*, a surface texture with a high aspect ratio. The relationship between the surface and the ball end cutter is shown in Fig. 5. The tool center, O, of the ball end cutter is on the line of the surface normal, Ns, for the cutting points, CC. For three-axis machining of a textured surface on a plane, the tool axis vector is the same as the vertical vector (0, 0, 1), N, and the top point, CL, of the tool is calculated by rotating Ns to N around O.

If the CL data point is calculated based on the STL data, the tool may not move smoothly because the CL data are often not smooth.[8] This occurs because the normal vectors of the CL data on the triangle mesh are constant, and the relationships between adjoining meshes are not continuous. This is most apparent in locations where the slope of the surface is large. The phenomenon persists even after reducing the size of the triangle mesh. Therefore, a technique is required to smoothly connect the CL data so that the tool moves smoothly. First, the square mesh including cutting points is searched and smoothed using a technique proposed by Peters.[9] In this process, a Bezier patch including the X- and Y-values of the cutting point is generated, and the Z-value and surface normal of the cutting point are modified to recalculate the CL data. The curve produced by connecting the cutting points becomes smooth.

4.3 Generation of CL data over a wide area and mapping to a geometrical surface

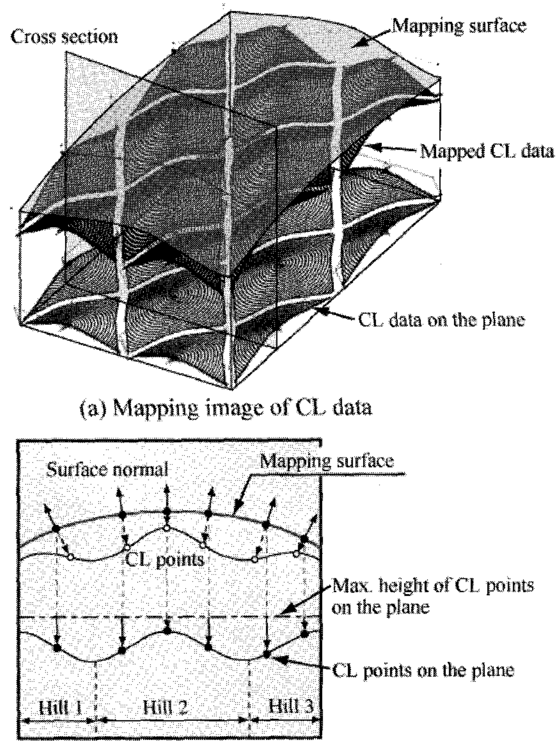


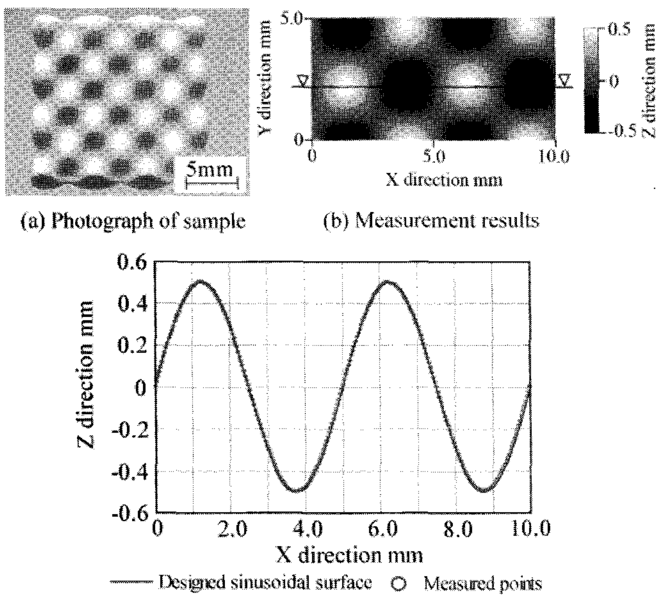
Fig. 7 Mapping of CL data to a geometric surface

Wide-area CL data were generated by connecting the CL data of each hill with the same shape generated in the manner previously described. Such a generated image is shown in Fig. 6, which contains an example of a regular garter stitch pattern consisting of several basic shapes with eight hills. The CL data for each of the eight hills comprising the basic shape were calculated only once. The wide area CL data were generated by connecting the CL data of multiple instances of this basic shape.

Machining the texture on the geometrical surface requires mapping the texture to the surface. The mapping method proposed in this study is shown in Fig. 7. We assumed that the slope on the geometrical surface was relatively small so as not to change the surface area on the plane or on the geometrical surface. The difference in height between the highest point of the CL data and each CL point on the plane was offset on the mapping surface normal to the surface. The tool vector on the plane, N, changed to the surface normal on the geometrical surface when mapping the CL texture data.

5. Machining test and assessment of machined texture

This section described the results of texture surface machining using the processes described above. The examples are shown on a plane for quantitative assessment.



(a) Photograph of sample (b) Measurement results

(c) Comparison of design data and measurement data

Fig. 8 Results for a sinusoidal surface

A simple regular pattern, *i.e.*, a sinusoidal surface, is shown in Fig. 8. This texture pattern consists of 24 hills with two different basic shapes, as shown in Fig. 8(a). The equation of this sinusoidal surface is

$$z = A\sin(x/\lambda x - \phi x)\sin(y/\lambda y + \phi y)$$

where $A = 0.5$ mm, $\lambda x = \lambda y = 2.5 / \pi$ (mm), and $\phi x = \phi y = 1.5\pi$. Therefore, the amplitude and wavelength of this curve are 0.5 mm and 5.0 mm, respectively. The pattern of the machined texture follows the design values given in Fig. 8(b). Figure 8(c) shows the profile of the design curve and the measured points; they agree closely.

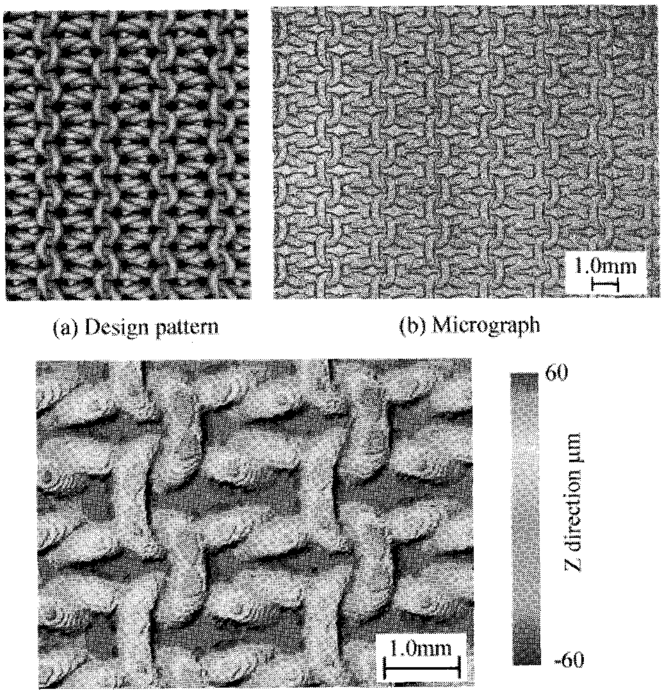
Examples of complex texture patterns are shown in Figs. 9 and 10. Figure 9 shows the garter stitch pattern, which consists of a basic connection pattern with eight hills. Figure 10 shows the rib pattern, which consists a basic connection pattern with six hills. Both machined samples corresponded closely to the design pattern, and the difference in height from top to bottom for both patterns was approximately 100 μm. The experimental conditions of these examples are shown in Table 1.

6. Conclusions

We described a means to generate surface textures with regular patterns. The proposed technique could be used to machine a wide area texture having many hills of several hundred μm in height with better precision than conventional processes such as etching or sandblasting. The shape of the machined textures corresponded well to the design pattern. In the future, we will extend the proposed method to the machining of textures on geometrical surfaces by five-axis milling.

Table 1 Experimental conditions

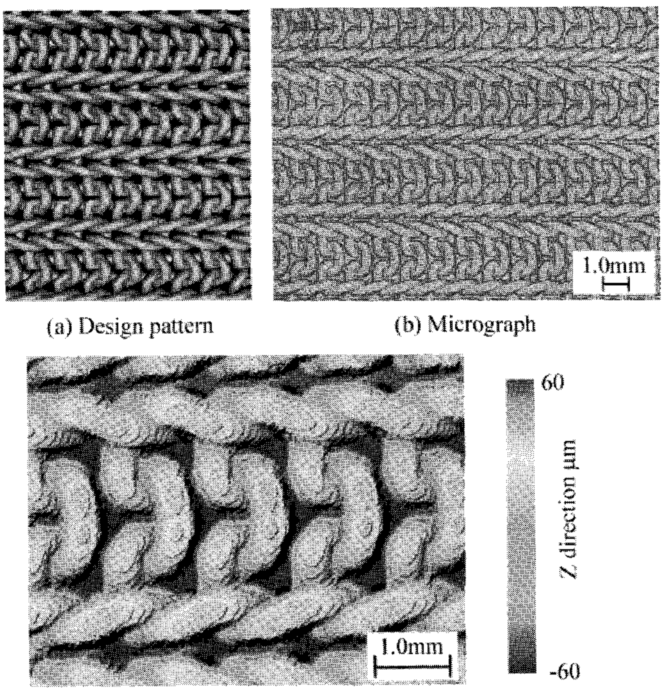
	Fig. 8	Fig. 9	Fig. 10
Texture pattern	Sinusoidal	Garter stitch	Rib
Spindle speed, rpm	14,000	60,000	
Feed rate, mm/min	800	300	
Radius of ball-end cutter, mm	1.0	0.1	
Material	Aluminum	Copper	



(a) Design pattern (b) Micrograph

(c) Measurement results

Fig. 9 Results for garter stitch pattern



(a) Design pattern (b) Micrograph

(c) Measurement results

Fig. 10 Results for rib pattern

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