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5th CIRP CSI 2020

Manufacturing of three-dimensional optical functional surfaces by diamond engraving of RSA 905

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Abstract

Functional surfaces have been investigated widely due to different applications in industries. In this paper, the surface functionality was the contrast generated by surfaces orthogonally textured with micro ridges. The principle to generate contrast was the anisotropic reflection led by the bevel surfaces of micro ridges. The surface quality of the micro bevels determined the reflection of the features. In the authors’ previous work, such a functionality was successfully achieved on flat and cylinder surfaces of tool steel samples by micro milling. However, due to the limitation of micro milling process for microstructure fabrication, this study investigated the manufacturing of 3D functional surfaces of RSA 905 by diamond engraving. The 3D surface was shaped with hierarchical structures of micro bricks and micro ridges on the bricks: the surface was divided into micro grids then each grid was machined into a flat basic cell by using a round-tipped tool; the micro ridges were engraved on the basic cells with a sharp-tipped tool. In order to determine the feasibility of the microstructures to achieve contrast generation on 3D surfaces, a data matrix consisting of such micro ridges was patterned on a spherical concave and a freeform surface. The surface integrity was evaluated by measuring the surface roughness of the bevels on the micro ridges, characterizing the bur formation and detection of possible defects left on the micro features that affect the surface functionality. The successful scanning of the data matrix proved the microstructures successfully generated enough contrast to form readable codes. Furthermore, the contrast generated by the microstructures was quantified for process optimization by using a customized robotic measuring system.

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Keywords: diamond machining; functional surface; hierarchical structures

1. Introduction

Functional surfaces have been investigated widely for different applications such as bio-engineering [1, 2], chemical [3], optical [4] and mechanical production [5, 6]. For example, the report by Chris J. Evans and James B. Bryan [7] presented the manufacturing of different kinds of structured surfaces and their applications; A. A. G. Bruzzone et al gave a comprehensive report exploring the relationships between the functional properties, manufacturing and applications [8].

Diamond machining applied in the manufacturing of optical functional surface and the characterization of resultant surface quality were studied in depth. The works on the diamond machining of the radial Fresnel lens on roller moulds and the evaluation based on the surface roughness and 3D profile of the corresponding lens were reported by [9,10]. X. Zhang et al utilized diamond micro engraving to machine the gravure roller mould for roll-to-roll printing of fine line electronics and the application in real production [11]. E. Brinksmeier and L. Schonemann presented the application of the diamond micro chiseling to generate discontinuous microstructures and associated the surface finish with the structure size [12]. More generally, F. Z. Fang et al reported the state of art of the manufacturing and measurement of freeform optics where they discussed the applications and presented different
manufacturing and characterization methods of verities of freeform surfaces [13].

In this paper, the surface functionality was the contrast generated by surfaces orthogonally textured with micro ridges. The principle to generate contrast was the anisotropic reflection led by the bevel surfaces of micro ridges, as introduced in [8]. The surface quality of the micro bevels determined the reflection of the features. In the authors’ previous works, such a functionality was successfully achieved on flat and cylinder surfaces of tool steel samples by micro milling [14,15].

This paper presents the evaluation of surface integrity of the surface and the three-dimensional (3D) optical functionality of the surface machined by the diamond machining. In order to understand the feasibility of the microstructures to achieve contrast generation on 3D surfaces, a data matrix consisting of such micro ridges was patterned on two samples: a spherical concave and a freeform surface. The surface integrity was evaluated by measuring the surface roughness of the slopes on the micro ridges, characterizing the burr formation and detection of possible defects left on the micro features that affect the surface functionality. The contrast generated by the microstructures was quantified for process optimization by using a customized robotic measuring system [14-16].

2. Surface evaluation

2.1. Evaluation of surface functionality

In this experiment, a model as shown in Fig. 1 (a) was developed to detect and quantify the contrast. The model was inspired by the code scanning process by mobile phones, consisting of three important elements: a fixed light source, functional surface sample, and a camera.

In order to build a more universal platform, the relative position of the camera and the light source was adjustable. The sample was located at the center of the system and light source was fixed above the sample; the camera covered a semi-spherical range above the sample by rotating and inclining about it. During the measurement, the light from the fixed light source was scattered to the semi-spherical range. For a certain setup, the intensity of reflected light observed by the camera was a function of the inclination angle \( \theta \) and the rotation angle \( \phi \):

\[
f = \text{reflection}(\theta, \phi), \quad \theta \in [0^\circ, 90^\circ], \phi \in [0^\circ, 360^\circ]
\]

(1)

In the authors’ previous work [14,15], the microstructures were machined in the directions aligned with the \( x \)- and \( y \)-axis, which formed the black and white modules of a code, respectively. In this paper, the textured and raw areas were defined as the black and white modules of a code. At certain viewing angles, the reflection of the textured area received by the camera reaches the peak while that of the raw areas zero. Thus, for the black and white modules, the difference in the reflection intensity received at the same position \( (\theta,0) \) was defined as contrast, see equation (2).

\[
\text{contrast}(\theta,0) = \text{exposure}_{\text{black}}(\theta,0) - \text{exposure}_{\text{white}}(\theta,0), \quad \theta \in [10^\circ, 70^\circ]
\]

(2)

![Image](a) Model of contrast evaluation

![Image](b) Customized robot-aided system for contrast evaluation

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2.2. Evaluation of surface quality

A confocal microscope Olympus Lext OLS4100 was used to evaluate the quality of microstructures. A 50X magnification was used and an area of 258x258 µm² was captured at one scan, including five micro ridges, as shown in Fig. 2 (a). Then the data was analyzed in a commercial post processing software SPIP. The width, depth, and slope angle of the micro ridges and the surface roughness of the slopes of the micro ridges were measured based on three cross sections along the cutting direction, as shown in Fig. 2 (b). The burrs formed at the ridge top and the exit was characterized by measuring the height. Since a 10 by 10 data matrix was patterned on the sample. Therefore, five structured modules at random position of the code was selected to evaluate the quality of the entire sample.

3. Experiments

3.1. 3D structuring for anisotropic surface functionality

The optical functional surface that relied on micro ridges to achieve anisotropy used surfaces on these micro ridges to reflect light directionally. The key to achieving a unified directional reflection was that these surfaces being parallel with each other. Since the curvature of each position is different on a 3D surface, it is difficult to directly pattern micro ridges to such surfaces.

Therefore, a compromise method was adopted to deploy the micro ridges on the surface as demonstrated in Fig. 3. First, a grid with a cell size of 200 µm was applied on the xy plane, which dividing the 1 x 1 mm² 3D surface into 200 x 200 µm² areas from top view. Second, the 3D areas were replaced with flat basic cells to form staircase structures; the height of each cell was the lowest point of the corresponding 3D area. As a result, the originally continuous and smooth 3D surface was transformed to discontinuous, staircase structures. Last, above-mentioned micro ridges were machined on the basic cells as marked in the figure. In this way, a two-layer (staircase structure and micro ridge) hierarchical structure was formed to replace the continuous surface without destroying the original shape of the 3D surface macroscopically.

In addition, with this transformation, the encoding by micro ridges on 3D surface was consistent with that on 2D samples. As shown in Fig. 4, a data matrix carrying a text string "123456" was patterned in this experiment. The black modules were full of micro ridges, while the white modules were un-machined. The dimensions of the microstructures are also indicated in Fig. 4. For the 3D case, at most four micro ridges were machined on a basic cell.

3.2. Experimental setup of diamond machining

The experiments were performed on a Nanotech 350FG with a programming resolution and motion accuracy of 0.01 nm and 12.5 nm, respectively [17]. The setup in the machine is demonstrated in Fig. 5. Two tools were used in the two stages of processing: a round-tipped tool was used for shaping for staircase structures and a sharp-tipped tool for the subsequent micro-structuring. The specifications of both tools are shown in Table 1. The work piece material was an injection moulding insert of RSA905 from RSP, the Netherlands [18]. Ethyl alcohol was used in the form of mist coolant to remove the generated chips from the sample surface. The feed speed was 150 mm/s in y- axis while other parameters were determined by the machine based on the tool path.
In practice, due to the clearance angle of 15°, the tool was tilted by 15°, in order to produce a cut-in angle of 30°, as indicated in Fig. 4. In addition, during the processing, due to the existence of the clearance angle, the surface can only be processed from a lower to a higher position. Therefore, the surface was measured in prior to the machining process. The tool path was generated by defining the key points in Matlab.

### Table 1. Tool specifications.\[19\]

<table>
<thead>
<tr>
<th>Tools</th>
<th>P90LEi</th>
<th>N0.50mLEi</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diamond type</td>
<td>Natural</td>
<td>Dodec synthetic</td>
</tr>
<tr>
<td>Tip</td>
<td>Sharp point</td>
<td>Round tip</td>
</tr>
<tr>
<td>Nominal tip radius [mm]</td>
<td>0</td>
<td>0.5</td>
</tr>
<tr>
<td>Included angle [°]</td>
<td>90</td>
<td>N.A.</td>
</tr>
<tr>
<td>Rake angle [°]</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Clearance angle [°]</td>
<td>15</td>
<td>15</td>
</tr>
</tbody>
</table>

**4. Results and discussion**

As shown in Fig. 6, the microstructures machined on the surface successfully achieved the desired surface function. The contrast was sufficient for the code to be recognized. The injection molded replicas was also scanned successfully.

Fig. 6. The code patterned on a spherical concave surface and the IM replica.

Fig. 7 (a) shows a 2D sample with 10° micro ridges on the platform described in Section 2.1. It can be seen that the reflectance differed with the camera inclination angle $\theta$, as expected, when the camera was at 20°, the reflection of the microstructure was the best.

The exposure of every module was obtained from the system. Then, the average exposure values of all the white modules and that of all the black modules were calculated for every inclination angle. Thus, the average contrast between the black modules and the white ones are plotted against the camera inclination angle in Fig. 7 (b).

The contrast reached a maximum value (0.025 J/m²) at 18°, then decreased dramatically after 20°. This verifies what is shown in Fig. 7 (a). The angle range of high contrast indicates that the consistency of the micro ridges. The narrower the range is, the better the features were machined. The ideal scenario is that the contrast is distributed in a narrow range around 20°. However, from Fig. 7 (a), the code was clear to see at even 50° while the values obtained from the system as plotted in Fig. 7 (b) kept zero after about 25°. It indicates that the processing procedure of the contrast measurement system still needs further adjustment.

![Contrast graph](image)

(b) Contrast generated by the modules structured with the orientation of 0° (white) and 90° (black).

Fig. 7. The sample under different viewing angles and the contrast generated.

Moreover, in order to optimize the machining process by contrast, the quality of the microstructure was evaluated to link the diamond machining parameters to the surface functionality. The surface roughness, width, depth, slope angle of the bevels on the micro ridges and burr height were measured and the results are shown in Table 2.
Compared with the flat modules (Sa = 5 nm), the surface roughness of the bevels of the micro ridges was about 12 nm, which indicated the quality of the micro ridges was lowered by the machining method. According to the dimensions of the micro ridges in Fig. 4, it can be calculated that the slope width and depth were 49.2 µm and 8.6 µm, respectively. This shows that there were obvious fluctuations during cutting, which can be seen from the structure shape in Fig. 2.

Similarly, the slope angle was less than 10° due to the vibration of the tool during the machining process or the accuracy of the tool presetting. The observation angle of the maximum contrast corresponding to 9.6° is about 19.2°, which is also consistent with the measurement of contrast, where the maximum contrast occurred at 18°. The burrs mainly formed in locations with lower depths, as shown in Fig. 2, so it was expected that the burrs could be reduced by reducing the vibration.

5. Conclusions

This paper introduces the process of using diamond machining to produce 3D optically functional surfaces and the evaluation of the surface quality and surface functionality. Both 2D and 3D samples were successful obtained. The surface function, the contrast, was quantified by a customized measurement system, and the results proved that the function of the microstructure was achieved: the contrast was sufficient for the code to be scanned; the microstructure with a slope angle of 10° reached the maximum contrast at the viewing angle of 20°. The contrast was associated with the quality of diamond machining process, through the quality evaluation of the integrity of the machined functional surface. The observing angle of the maximum contrast was associated with the actual slope angle of the micro ridges.

Future work will be dedicated to the quantitatively associate the surface functionality and the diamond machining process. Moreover, the injection molding experiments of the diamond machined inserts will be conducted to understand the durability of the microstructures and the fidelity of the surface functionality.

Table 2. The surface quality of the sample with 10° of slope angle.

<table>
<thead>
<tr>
<th>Sa</th>
<th>Width</th>
<th>Depth</th>
<th>Burr height</th>
<th>Slope angle</th>
</tr>
</thead>
<tbody>
<tr>
<td>12 nm</td>
<td>46.0 µm</td>
<td>7.9 µm</td>
<td>0.4 µm</td>
<td>9.6°</td>
</tr>
</tbody>
</table>

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Acknowledgements

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