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Nano-precision fabrication of hexagonal microlens array by segment turning using slow tool servo

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Abstract

Diamond turning with a slow tool servo (STS) is widely used to generate continuous freeform surfaces, but is difficult to machine discontinuous surfaces having sharp edges, such as microlens array, because of dynamic problems. In this study, we propose a new STS diamond turning method named "segment turning", in which the micro dimples are selectively divided into multiple groups, and each group of dimples are machined in a single turning cycle. In this method, the *Z*-axis acceleration can be decreased sharply, which reduces dynamic error of the machine tool. As a result, the segment turning method improved the form accuracy greatly compared to conventional turning method within the same machining time. As a test piece, a hexagonal microlens array was successfully fabricated with nanometer level precision.

Keywords: structured surface, ultra-precision machining, slow tool servo, diamond turning, microlens array

1. Introduction

Microlens arrays are increasingly demanded in advanced high-integration and high-performance optical systems. Especially, a hexagonal microlens array has excellent optical performance because it offers a fill factor of 100 % [1]. Fast tool servos (FTSs) are useable for generating shallow lens arrays, but difficult to cut deep lens arrays. Raster milling is useable in case of fabricating deep hexagonal microlens arrays. However, it is difficult to guarantee the form accuracy and the machining process is very time consuming [2].

In this work, we use diamond turning to generate hexagonal microlens array molds where the diamond tool is driven by a slow tool servo (STS). STSs have been widely used to generate continuous freeform surfaces, but have not been widely used to machine discontinuous surfaces having sharp edges, such as microlens arrays, due to dynamical problems of machine tools caused by the excessive acceleration of *Z*-axis machine tables. In this study, we present a new STS diamond turning method named "segment turning" to machine discontinuous surfaces having sharp edges, such as hexagonal microlens arrays.

2. Segment turning method

Figure 1(a) shows the schematic of an ultraprecision diamond turning lathe having a STS system, and Figure 1(b) shows freeform surface machining by using the STS system, where the *Z*-axis position of the tool is synchronized with the *C*-axis

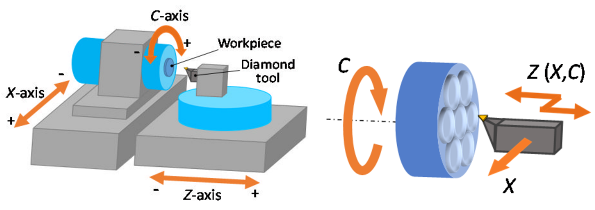


Figure 1. Schematic of STS diamond turning (a) diamond turning lathe, and (b) machining process

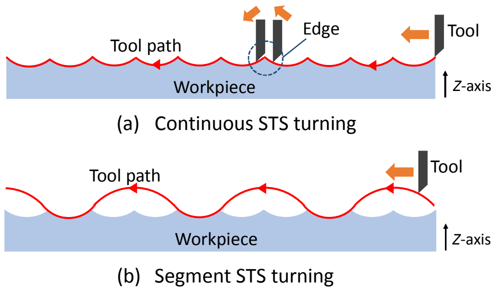


Figure 2. Tool path of STS turning of microlens array molds

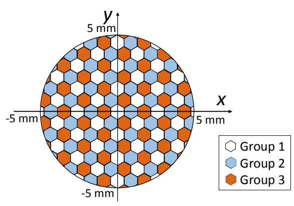


Figure 3. Designed shape and schematic of segment

rotation of the workpiece. Conventionally, when machining microlens array molds, all lenslets are machined in single turning cycle continuously, namely, continuous STS turning, as shown in Figure 2(a). This method leads to excessive *Z*-axis acceleration at the sharp edges, and causes dynamic errors of the machine tool. In this study, segment STS turning is proposed, as shown in Figure 2(b). In this method, the lenslets are divided into multiple groups where the lenslets in each group are separate from each other, and each group of lenslets are machined in a single turning cycle. In this way, the sudden change in direction of the tool path is avoided, which reduces *Z*-axis acceleration and improves the motion accuracy of the machine tool.

3. Experimental procedures

As test cuts, hexagonal microlens arrays were machined on aluminum alloys by continuous STS turning and segment STS turning, respectively. An ultra-precision diamond turning lathe Precitech Nanoform X was used in the experiments. A roundnosed single-crystal diamond tool with a nose radius of 0.1 mm and rake angle of 0° was used. The workpiece was 10 mm in diameter, and each lenslet has a concave hexagonal shape with a side length of 500 µm and a sag of 5 µm. Figure 3 shows the designed shape of the lens array and distribution of divided lenslet groups in segment turning. The whole lens array was divided into three groups which were cut sequentially. The spindle rotation rate in segment turning was 45 rpm, while that in continuous turning was 45 rpm and 15 rpm. Tool feed per workpiece revolution was 1 µm, and depth of cut was set to 2 µm for the finish cutting.

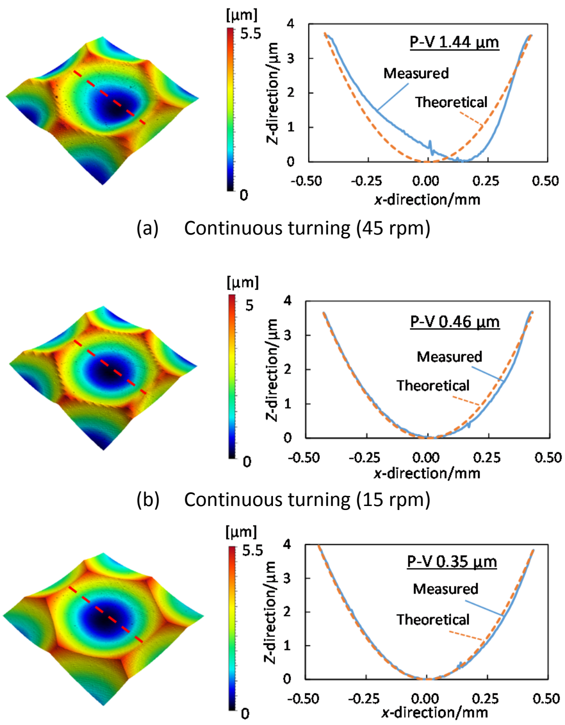
4. Results and discussion

4.1. Lens shape measurement

The profiles of machined lens were measured using a laser-probe profilometer NH-3SP (Mitaka Kouki Co., Ltd.). Figure 4 shows three-dimensional topographies of the lenslet the center of which is located at x=0 mm, y=1.5 mm in Figure 3, and cross-sectional profile along x-axis passing through the center of the lenslet (red dashed line in the three-dimensional topography). The results show that the peak-to-valley (P-V) value of the cross-sectional profile error in segment turning was 24 % of that in continuous turning at the same spindle rotation rate (45 rpm), and 76 % of that in continuous turning during the same machining time but at a lower spindle rotation rate (15 rpm).

4.2. Z-axis acceleration of machine tool and dynamic error

Figure 5 shows the position error between program command and actual position in Z-axis, and Z-axis command acceleration measured during a period of 0.75 second after the tool passing the point X=1.5 mm. The P-V value of Z-axis position error has the same tendency as the P-V value of lens form error in Figure 4, which means the lens form error was mainly caused by the dynamic error of the machine tool. In continuous turning, the absolute value of acceleration at lenslet edges was so large that it led to a delay in Z-axis motion of the machine table. However, in segment turning, the acceleration was reduced by a factor of five compared to that in continuous turning at the same spindle rotation rate, which accordingly reduced position error. Even the Z-axis acceleration can be reduced by decreasing the spindle

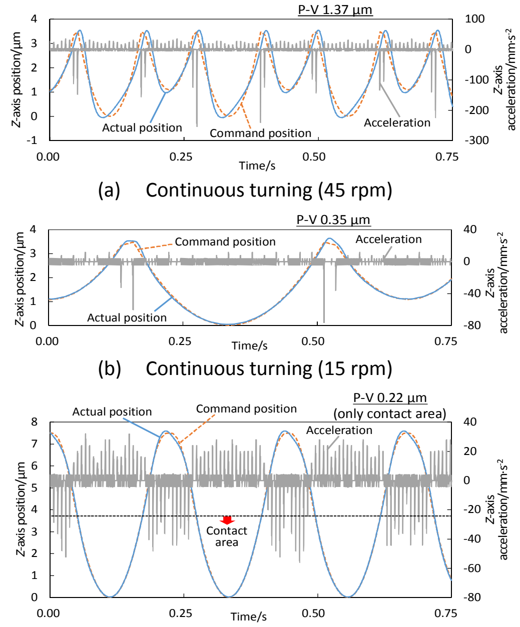


(a) Continuous turning (45 rpm)

(b) Continuous turning (15 rpm)

(c) Segment turning (45 rpm)

Figure 4. Three dimensional shape and cross section profile of lenslet

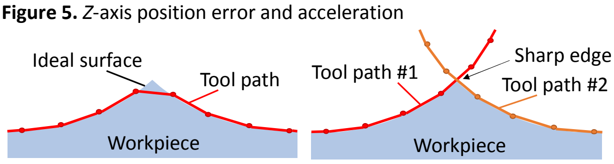


(a) Continuous turning (45 rpm)

(b) Continuous turning (15 rpm)

(c) Segment turning (45 rpm)

Figure 5. Z-axis position error and acceleration



(a) Continuous turning (b) Segment turning

Figure 6. Tool path at lenslet edges

rotation rate, the acceleration at lenslet edges in segment turning was significantly lower than that in continuous turning.

4.3. Effects of linear interpolation on edge sharpness

As shown in Figure 6, STS turning generates freeform surfaces by calculating coordinates of a finite number of points on the objective surface and interpolating linearly between these points. Thus, different tool path will be generated at lenslet edges in different turning methods. In continuous turning, the distance between multiple points is limited and depends on the processing speed of machining program. As a result, sharp edges cannot be formed when the number of coordinate points is not adequate to envelope the edges, as shown in Figure 6(a). In segment turning, however, the tool path is not affected by linear interpolation, as shown in Figure 6(b), which improves edge accuracy. This agrees well with the experimental results of edge sharpness in Figure 4.

5. Conclusions

Segment turning using STSs was proposed for machining discontinuous microstructures with sharp edges, such hexagonal micro lens arrays. Compared to continuous turning, the form error of microlens array was reduced to 24 % and 76 % of that in continuous turning at the same spindle rotation rate and the same time, respectively. Extremely sharp edges were generated because of the reduction in Z-axis acceleration and the improved tool path at lenslet edges.

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