Fast fabrication of Si microlenses combined with ultrasonic elliptical vibration sculpturing and in-situ laser assisted diamond cutting

Xinhuan Li[1], Haoqi Luo[1], Jiaxin Hao[1], Jianguo Zhang[1] and Jianfeng Xu[1,#]

1 State Key Laboratory of Intelligent Manufacturing Equipment and Technology, School of Mechanical Science and Engineering, Huazhong University of Science and Technology, Wuhan, 430074, China

Corresponding Author / Email: jfxu@hust.edu.cn, TEL: +86-15972166389

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Single crystal silicon has been widely used in aerospace and optical detection due to its excellent properties. The functional microstructure can furtherly improve the system performance. In the present work, the ultrasonic elliptical vibration sculpturing was adopted to fast fabrication of microlenses on silicon. To avoid tool wear and obtain better surface quality, in-situ laser was added to reduce the hardness of single crystal silicon. Hence, the fabrication of microlenses based on ultrasonic elliptical vibration sculpturing and in-situ laser assisted cutting was proposed. The experimental achievements verified the high precision functional microstructure fabrication with excellent surface uniformity. The structural height of microlenses was 342 nm, which was close to the critical ductile-to-brittle transition depth of cut by applying laser assisted cutting. This novel technology is proposed to manufacture the functional microstructure surface of hard-brittle materials efficiently.

NOMENCLATURE

h = the height of the microlenses

1. Introduction

Single crystal silicon (Si) has received extensive attention because of its excellent physical and chemical properties under extreme conditions [1], which is widely used in the fields of optical systems. Moreover, as one of the functional optical microstructures, microlenses provide with the benefits of miniaturization, lightweight, and excellent service performances. The microlenses are fabricated by the popular slow tool servo technology in the diamond cutting process, which is with low efficiency [2]. Ultrasonic elliptical vibration assisted cutting (UEVC) was proposed by Shamoto and Moriwaki [3]. In the UEVC process, the tool vibrates elliptically in the plane composed of the cutting direction and depth of cutting direction. Yang fabricated color patterns on metal surfaces by precisely controlling the speed of the feed direction and the cutting direction using UEVC [4]. Suzuki proposed a vibration-assisted micro-cutting technique with controllable amplitude variations, forming target microstructure surfaces by controlling the amplitude changes in the cutting depth direction [5]. Hence, the ultrasonic elliptical vibration locus can be used to fabricate microstructures efficiently.

However, as a hard -brittle material, Si is difficult to be machined by traditional methods, which lead to severe tool wear, low machining accuracy and poor surface finishing quality [6]. Laser assisted cutting (LAC) is a promising method for machining Si. The apparent hardness of the machined material can significantly decrease by focusing the laser beam on the cutting area [7], which enables the material to be removed from the ductile region [8]. Laser assisted cutting (LAC) can reduce cutting force effectively and extend tool life compared to ordinary cutting [1]. Geng proposed LAC could improve the processing surface quality of materials and reduce residual stress on material surface [9]. Guo showed that LAC had the abilities of improving surface quality, increasing material removal rates, and reducing surface roughness on machining Si [10].

In the present work, microlenses on Si were fabricated by applying UEVC and LAC. The vibration locus was used to form microlenses on softened Si, which was caused by LAC. In this way, microlenses were fabricated efficiently on hard-brittle materials.

2. Plane cutting experiment of Si

2.1 Experimental setup

In order to fabricate microlenses on Si, a flat plane of Si is necessary for obtaining a reference machining surface. The experimental platform consists of a four-axis ultra-precision machine tool (Precitech Nanoform X, USA), and the self-developed in-situ laser-vibration hybrid assisted cutting (ILVC), as shown in Fig. 1. The crystal plane of Si used in this experiment is <100>. The diamond tool with a 0.5 mm round nose radius, -35° rake angle, and 10° clearance angle was used as the cutting tool. The processing parameters are shown in table 1. The spindle rotation speed was 200 rpm/min.

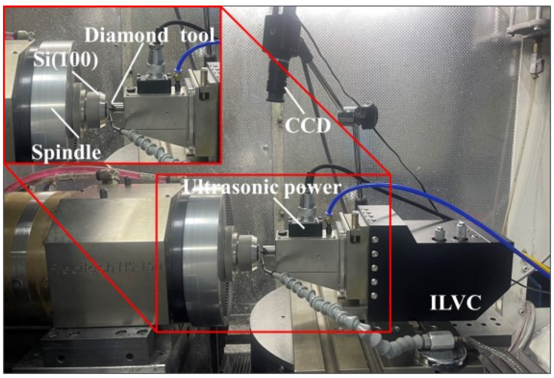

Fig. 1 Experimental setup

Table 1 Parameters of plane cutting experiment

Cutting parameters	Data
Cutting speed	2000rpm/min
Feed speed	5μm/r
Cutting depth	2μm
Workpiece diameter	5.4mm

2.2 Results and discussion

The machined surface of Si is shown in Fig. 2, which has the surface roughness of Ra 3.387 nm. There is no obvious brittle defects on the machined surface. The optical image of the diamond tool after machining is shown in Fig. 3. The diamond tool has a slight wear with 47.7 μm length, which was used to cut 3 times cycle. It shows the excellent surface of hard and brittle materials was obtained by applying LAC, and the tool wear was significantly inhibited.

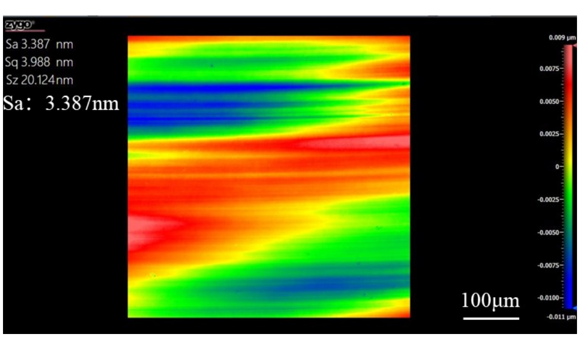

Fig. 2 Machined surface of Si

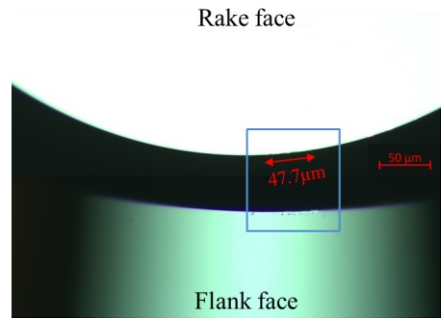

Fig. 3 The surface of diamond tool after plane cutting

3. Fabrication of microlenses on silicon

3.1 The forming process of microlenses

As shown in Fig. 4, the tool vibrates elliptically in the plane composed of the cutting direction and depth of cutting direction. As the workpiece rotates, the diamond tool cuts the microlens on the surface of Si. The shape of the microlens is determined by the cutting speed. The height of the microlens h is determined by the amplitude of the cutting depth direction and the cutting depth. While serious tool wear occurs when diamond tools cut hard and brittle materials. Hence, in-situ laser is used to soften the material as microles fabricated. However, some second-order discountinuies of lens curvature may occur during orbital radius changing.

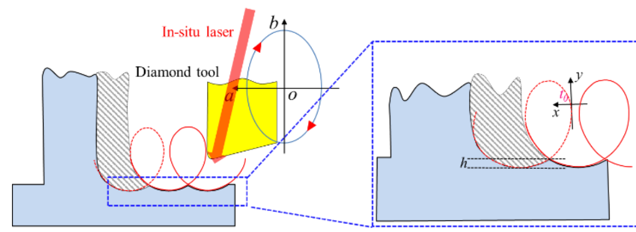

Fig. 4 The forming process of microlenses

3.2 Experimental setup

To verify the feasibility of the proposed machining method, as shown in Fig. 4, a self-developed ILVC was used to fabricate microlens on Si as shown in Fig. 1. The diamond tool with a 0.5 mm round nose radius, -35° rake angle, and 10°clearance angle was the cutting tool. The detailed machining conditions are listed in Table 2. The nominal cutting speed was 90 m/min.

Table 2 Parameters of microlenses manufacturing

Cutting parameters	Data
Workpiece diameter	5.4mm
Cutting speed	90m/min
Feed speed	80μm/r
Laser power	3W
Processing time	5s

3.3 Results and discussion

The three-dimensional morphology of microstructures on the surface of Si was measured using a White Light Interferometer (Zygo NewView 9000), as shown in Fig. 5. It can be observed that, the surface of Si has successfully achieved high precision in functional microstructure processing, with well surface uniformity. The height of microlenses is 342 nm, which is much larger than the cutting depth of ordinary cutting. In the process, LAC increases the plastic cutting ability, thereby providing more possibilities for ultra-precision manufacturing. This manufacturing method has high efficiency, which fabricate 35000 microlenses in a second. And the diamond tool has no obvious wear as Fig. 6, which ensures large-scale microlenses manufacturing.

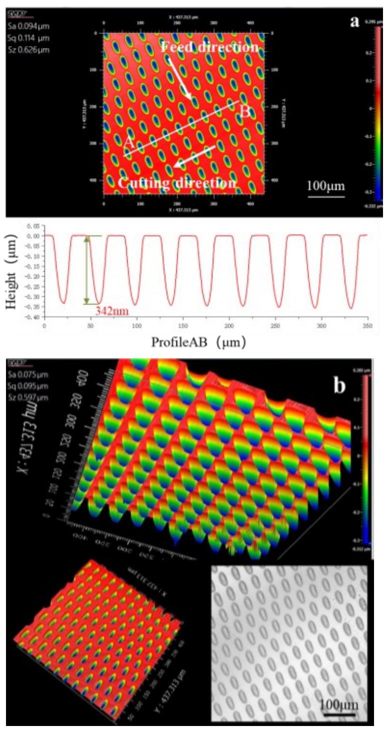

Fig. 5 The 2D (a) and 3D (b) morphology diagram of microlenses

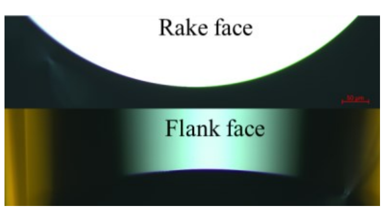

Fig. 6 The surface of diamond tool after fabricating microlenses

4. Conclusions

This study proposes a method to fabricate microlenses combined with ultrasonic elliptical vibration sculpturing and in-situ laser assisted diamond cutting. Experiments on plane cutting and fabrication of microlenses were carried out. The following conclusions were obtained:

1. LAC can obtain better surface of Si, and effectively inhibit tool wear. The softening effect of in-situ laser is beneficial for machining hard-brittle materials.

2. UEVC can process microlenses efficiently. Furthermore, the add of in-situ laser can realize the high efficiency microlenses machining of Si.

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