Fast fabrication of microlens array on single crystal Si by in-situ laser and elliptical vibration hybrid diamond cutting

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Microlens arrays on single crystal silicon (Si) are promising for enhancing the integration and lightweighting of advanced optoelectronic systems. However, there are still challenges of low surface quality and low machining efficiency in single crystal Si microlens array diamond cutting due to the hard and brittle properties. In-situ laser assisted diamond cutting has proven to be an effective method in the ultra-precision machining of hard and brittle materials by softening the material, improving the material ductility and suppressing the tool wear through the irradiation of in-situ laser. Besides, the elliptical vibration texturing process enables fast generation of microstructures through coupling the high-frequency vibration trajectories and the tool geometry. In this study, a method of fabricating single crystal Si microlens arrays combining in-situ laser softening and elliptical vibration texturing process is proposed for improving the material ductile machinability and processing efficiency. Firstly, a microlens arrays machined surface model was established considering the tool geometry, elliptical vibration trajectory and machining parameters. The relationship between the target profile and tool geometry, elliptical vibration trajectory, machining parameters was revealed. Then, the critical depth of cut under in-situ laser assistance for each orientation of single crystal Si was analyzed based on the helix scratching method. The maximum allowable sag of microlens without cracks in each orientation during the in-situ laser assisted diamond cutting process was calculated. Finally, the diamond cutting experiments of single crystal Si microlens arrays were carried out by an in-situ laser-vibration hybrid assisted diamond cutting system, and the microlens array was successfully fabricated on the single crystal Si in ductile mode with high efficiency. This work provides a valuable method for the fast generation of microstructure array on hard and brittle materials.

1. Introduction

Microlens arrays (MLAs) are series of lenses with micron-sized apertures and sag. They can realize the functions of beam shaping and imaging and support high integration and lightweighting of optical systems [1]. Diamond cutting technology has the advantages of high freedom and high efficiency, which has been widely used in the manufacture of MLAs [2]. Slow tool servo (STS) and fast tool servo (FTS) of diamond cutting have been proved to be effective methods for machining free-form surfaces [3]. However, the dynamic response frequency of STS and FTS is low, in which the maximum frequency of STS is generally 100 Hz and that of FTS is generally 10 kHz. The response frequency limits the fabrication efficiency of MLAs. Therefore, the rapid fabrication of high curvature microstructures remains a challenge.

The ultrasonic elliptical vibration cutting (UEVC) technology was proposed by Shamoto and Moriwaki [4]. In the UEVC process, the cutting tool vibrates elliptically at a frequency of about 40kHz and moves along the nominal cutting direction [5]. In addition, a part of vibration trajectory is superimposed on the machined surface in each vibration cycle, resulting in regular undulation on the machined surface. Guo and Ehmann [6] proposed to apply the unique property of regular undulations to surface texturization, and a series of layered sinusoidal and cubic surface arrays were successfully fabricated by applying relatively high nominal cutting speeds and constant elliptical vibration amplitudes [7]. Due to the higher frequency of motion and nominal cutting speed, the machining efficiency is higher than conventional diamond cutting techniques. However, the tool cannot be separated from the workpiece material in each vibration cycle, which is prone to severe tool wear and crack extension on the machined surface. Thus, this technique has not been applied to machining MLAs on hard and brittle materials, such as monocrystalline silicon (Si) [8].

During the past decades, laser assisted cutting (LAC) technology has become an important manufacturing method for the machining of hard and brittle material. The laser beam was focused on the cutting area, which significantly reduces the hardness and improves the plastic deformation of the material. It is advantageous to cutting the hard and brittle materials in the ductile regime [9]. To better control the energy of the focusing area, Ravindra et al. proposed an in-situ laser assisted cutting method [10]. The form of in-situ heating is applied by laser assisted to suppress the damage in diamond cutting. Fang et al. [11] and Xu et al. [12] indicated that the in-situ laser-assisted cutting technology can effectively improve the ductile machinability of hard and brittle materials. It has been experimentally verified that the hard and brittle materials including the Si [13], tungsten carbide [14] can be successfully machined with few cracks, lattice distortions, and other defects.

In summary, the combination of in-situ LAC and UEVC can provide a promising process for the fast fabrication of MLAs on hard and brittle materials. In this study, an in-situ laser- elliptical vibration hybrid cutting system is innovatively adopted to realize the efficient fabrication of Si microlenses. The combination of the in-situ laser softening and ultrasonic elliptical vibration trajectory simultaneously ensuring efficiency and profile accuracy in Si MLAs fabrication.

2.In-situ laser and ultrasonic elliptical vibration hybrid cutting technology

In-situ laser - vibration hybrid cutting (ILVC) process is shown in Fig. 1(a). During the cutting process, the high-frequency elliptical vibration trajectory of the tool generates periodic texture on the workpiece surface. The feature allows the microstructures to be fabricated with high efficiency. Synchronously, the laser beam irradiates on the cutting area after passing through the diamond tool, reducing the hardness and improving the ductile machinability of the material. Therefore, ILVC technology enable to further improve the machining efficiency and surface integrity of hard and brittle materials MLAs.

In this study, a series of experiments was carried out based on the self-developed ILVC system to investigate the fast fabrication of MLAs on single crystal Si, the experimental equipment is shown in Fig. 1(b). The collimated laser beam pass through the hollow luffing bar and focused on the diamond tool tip, The equipment couples the advantages of in-situ laser and ultrasonic elliptical vibration to realize the simultaneous action of cutting trajectory.

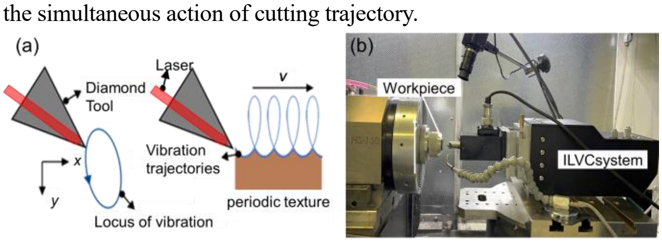

Fig. 1. Schematic diagram of cutting process (a) and experimental equipment(b)

3. MLA fabrication principles by ILVC

To generate the target microlens profile, the cutting trajectory of the ILVC device was analyzed firstly. The tool forms an elliptical trajectory vibration is excited by the piezoelectric ceramics with vibration along cutting direction and depth of cut direction. During the cutting process, the tool moves relative to the workpiece by spiral trajectory. The spiral trajectory is coupled with the high-frequency vibration trajectory to form the final cutting trajectory. Due to the high frequency of the ultrasonic vibration generated by the device, the cutting speed should be set high to separate each lenses.

The morphology of the machined microlens array is related to the cutting parameters, vibration parameters, and tool shape parameters. To establish a microlens array cutting trajectory model, theoretical calculation and simulation analysis were carried out. The cutting edge of the tool is semi-circular arc, and the coordinates of the tool profile can be expressed as:

$$x_{arc} = r \bullet \cos\theta_{arc} \tag{1}$$

$$z_{arc} = r \bullet \sin\theta_{arc} + z_1 \tag{2}$$

where x_{arc} and z_{arc} are the coordinate values of the tool arc, r is the diamond tool radius. θ_{arc} is the angle of the edge arc, and z_1 is the variable that adjusts the coordinates of the tool tip to the workpiece surface. Since the diamond tool tip has a certain angle, the rotation of the tool arc profile coordinates is required. During this process, the X-axis are not changed. The Y-axis and Z-axis can be expressed as:

$$x_{trans} = x_{arc} \bullet \sin(-\theta_q \bullet \pi / 180) \tag{3}$$

$$y_{trans} = y_{arc} \tag{4}$$

$$z_{trans} = z_{arc} \bullet \cos(-\theta_q \bullet \pi / 180) \tag{5}$$

Where x_{trans} , y_{trans} and z_{trans} are the transformed coordinate values and θ_q is rake angle of the diamond tool. And the cutting trajectory equation is:

$$y_{motion} = A_c \cos(2\pi ft) + vt \tag{6}$$

$$z_{motion} = A_d \cos(2\pi ft + \phi) \tag{7}$$

Where y_{motion} and z_{motion} are the coordinate values of the motion trajectory. A_c is the vibration amplitude along the cutting direction and A_d is the vibration amplitude along the cutting depth. f is the vibration frequency, ϕ is the phase shift and v is the cutting speed.

The theoretical shape of the MLAs can be obtained after inputting the required parameters into the established model. In this case, the cutting speed was set to 200 m/min, the frequency was set to 35 kHz, the vibration amplitude along depth of cut direction and cutting direction were set to 1 μm and 4 μm, respectively. The theoretical shape of the MLA was obtained as shown in Fig. 2. The profile1 is the profile along the cutting speed direction. The cutting trajectory in this direction is sinusoidal, composed by ultrasonic vibration and machine spindle motion. Profile 2 is the profile along the feed direction. The profile is the same as the radius of the tool tip nose, which is 0.5 mm.

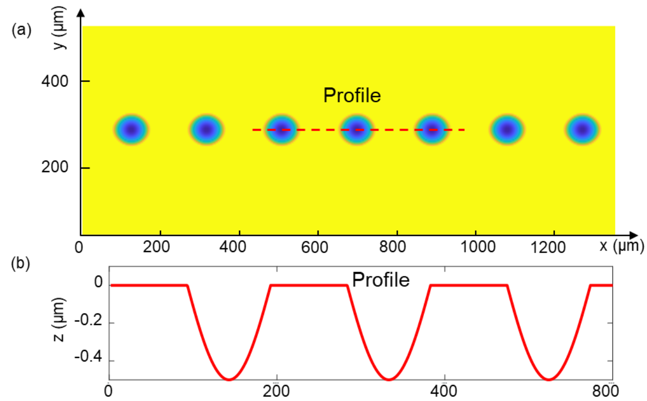

Fig. 2 (a): Simulation of MLA morphology and (b): Section line of Profile.

4.Experiments and results

4.1 Spiral grooving experiments

To realize the high quality manufacturing of the MLA, it is necessary to ensure that the machining is in ductile mode. Since the nominal cutting direction of the tool is spiral, all the orientation of Si will be cut during machining the MLA. Besides, Si is anisotropic and will exhibit different cutting properties along each cutting directions, thus it is important to determine the minimum critical depth of cut among all the orientation. Spiral grooving experiments was carried out to determine the process parameters for the minimum critical depth of cut among all the orientation in different condition, as shown in Fig. 3(a). The diamond tool moved along the Archimedes line and the depth of cut increased. The remove mode of Si gradually changes from ductile to brittle. The cross-section morphology of the groove is the same as that of the diamond tool, thus the critical cutting depth can be calculated by measuring the width of the groove . The process parameters are shown in Table 1.

Table 1 Parameters of annular trench experiment

Cutting parameters	Data
Cutting speed	200 m/min
Feed speed	120 μm/r
Cutting depth	0-2 μm
Laser power	3W,4W

The critical cutting depth distribution along different orientation was shown in Fig. 3(b). At a laser power of 3W, the maximum critical cutting depth is 420 nm, and the minimum critical cutting depth is 255 nm. At a laser power of 4W, the critical cutting depth distribution was similar to that of 3W. However, with the increase of the laser power, thermal ablation and thermal cracks appear on the surface, and the critical cutting depth decreases. Therefore, a laser power of 3W was chosen for the MLAs processing.

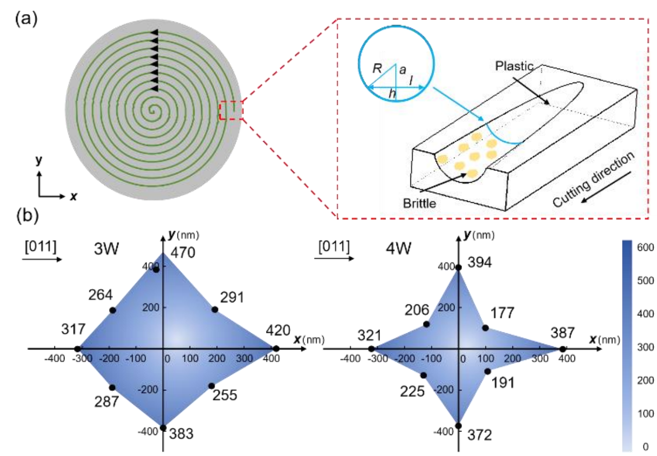

Fig .3 Schematic diagram of trench experiment (a) and critical cutting depth with different laser power (b)

4.2 MLAs fast fabrication experiments

To verify the feasibility of the proposed method, the MLAs was fabricated on Si by the self-developed ILVC, as shown in Fig. 1b. The diamond tool with a 0.5 mm round nose radius, -35° rake angle, and 10° clearance angle was utilized. The detailed machining parameters are shown in Table 2.

Table 2 Parameters of MLA cutting

Cutting parameters	Data
Workpiece diameter	25.4 mm
Cutting speed	120 m/min, 220m/min
Feed speed	8 μm/r, 120 μm/r
Laser power	3W
Processing time	3-5s

The three-dimensional morphology of the machining surface was measured by the white light interferometer (Zygo NewView 9000), as shown in Fig. 4. The results were consistent with the theoretical analysis. At a cutting speed of 120 m/min, the microlenses shape shows an ellipse and tightly aligned, as shown in Fig. 4(a). When the cutting speed is 220 m/min, the size and alignment spacing of the microlenses are larger, as shown in Fig. 4(b). Therefore, changing the cutting speed can change the arrangement spacing of the microlens array.

The experimental results show that the method successfully realizes high-precision microlens array machining on the single crystal Si. The microlenses have a uniform shape profile and excellent surface quality. The seg of the microlenses was about 300 nm, which is much larger than the critical cutting depth of 100 nm in ordinary cutting, and shows that the in-situ laser increases the ductile machinability. Since the microlens array was directly processed by high-frequency vibration trajectories, 35,000 microlenses can be fabricated in one second. The method improves the processing efficiency of MLAs on hard and brittle materials.

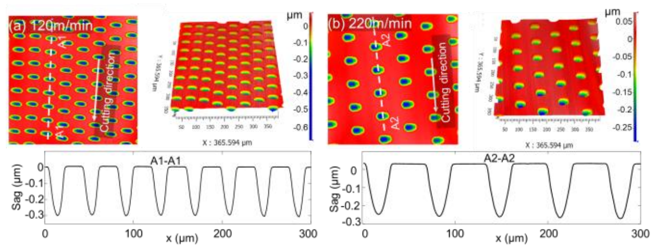

Fig. 4 Surface topography of microlenses with cutting speed of 120 m/min (a) and 220 m/min (b)

5. Conclusion

In this study, a fast fabrication method of MLAs on single crystal Si is proposed. The method combines in-situ laser softening and elliptical vibration texturing process for improving the material ductile machinability and processing efficiency. Firstly, considering the cutting parameters, vibration parameters, and tool shape parameters, the surface morphology model of MLA is established. The target contour is simulated according to the input parameters. then the maximum critical depth of cut was determined to be 420nm based on the spiral grooving experiments, ensuring that the machining is in ductile mode along all orientations. Finally, the MLAs were fabricated on single crystal Si by the self-developed ILVC. The MLAs have a uniform shape profile and excellent surface quality. The processing efficiency of fabricating MLA has been significantly improved. This work provides a new method for exploring the rapid generation of microstructure arrays on hard and brittle materials

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