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Weakening of the anisotropy of surface roughness in ultra-precision turning of single-crystal silicon

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Abstract Ultra-precision machining causes materials to undergo a greatly strained deformation process in a short period of time. The effect of shear strain rates on machining quality, in particular on surface anisotropy, is a topic deserving of research that has thus far been overlooked. This study analyzes the impact of the strain rate during the ultra-precision turning of single-crystal silicon on the anisotropy of surface roughness. Focusing on the establishment of cutting models considering the tool rake angle and the edge radius, this is the first research that takes into account the strain rate dislocation emission criteria in studying the effects of the edge radius, the cutting speed, and the cutting thickness on the plastic deformation of single-crystal silicon. The results of this study show that the uses of a smaller edge radius, faster cutting speeds, and a reduced cutting thickness can result in optimally uniform surface roughness, while the use of a very sharp cutting tool is essential when operating with smaller cutting thicknesses. A further finding is that insufficient plastic deformation is the major cause of increased surface roughness in the ultra-precision turning of brittle materials. On this basis, we propose that the capacity of single-crystal silicon to emit dislocations be improved as much as possible before brittle fracture occurs, thereby promoting plastic deformation and minimizing the anisotropy of surface roughness in the machined workpiece.

1. Introduction

Single-crystal silicon is the principal material used for solid-state electronics and infrared optical technologies. The anisotropy of single-crystal silicon surfaces plays a vital role since surface roughness has a considerable influence on both product quality and functional aspects. Explanations of surface anisotropy were given by Shibata[1] and Blackley et al.[2] from different angles, but no solution was provided. Pérez and Gumbsch[3] studied the cleavage fracture processes in silicon using total-energy pseudopotential calculations. They pointed

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out that the different lattice trapping for different crack propagation directions could explain the experimentally observed cleavage anisotropy in silicon single crystals. In recent years, the demand for surface perfection has continued to rise. Various efforts have been made to improve defects in silicon parts.[4,5] In order to improve the machinability of silicon parts, scholars have utilized different means in an attempt to understand the deformation, fracture, and microstructural changes of silicon.[6,7] For example, a recent work has demonstrated that nanosecond-pulsed laser irradiations can be used to reconstruct machining-damaged silicon substrates to perfect single crystalline structures, offering the possibility of a new processing technique for high-quality silicon wafers.[5]

Eric et al. revisited the rotating tool concept, firstly proposed by Shaw in 1952. This approach avoids the rapid degradation of diamond tools by constantly providing a fresh cutting edge. Eric et al.[8] concluded that the demand for precision in infrared optics would require that Shaw's original concept be enhanced with provisions for near-perfect cutting tool roundness and centering on a stiff, accurate axis of rotation. Cheung[9] noted that although some research progresses had been made on the effect of crystallographic orientation on surface quality, our technical know-how in regard to minimizing surface anisotropy during diamond turning of brittle single crystals was still far from perfect. In his paper, the effect of cutting friction on surface anisotropy in the diamond turning of brittle single crystals was investigated. Cheung then explored the relationship between the cutting friction and the anisotropy of surface roughness in the light of his experimental findings, while also discussing the implications of the findings on the minimization of surface anisotropy in the diamond turning of brittle single crystals. It was found that the anisotropy of surface roughness decreased whereas the mean arithmetic roughness increased with increasing cutting friction. The research results of other scholars investigating the mechanism of brittle ductile transition and the machinability of single-crystal silicon have also provided inspiration for reducing the anisotropy of surface roughness. In the work of Brian et al.,[10] the critical chip thickness for ductile regime machining of electronic-grade silicon was measured as a function of crystallographic orientation on the (0 0 1) cubic face. If a diamond turning operation was configured so that the critical chip thickness was somewhere between the [1 1 0] direction limit of 40 nm and the [1 0 0] direction limit of 120 nm, a four-lobed star damage pattern would be plainly visible in the finished workpiece. Vladislav et al.[11] noted that if the depth of cut was less than the depth of the transformed metallic phase, the material removal process would behave as expected for a ductile material. However, if the depth of cut was too aggressive and exceeded the dimension of the metallic phase, then the material would be removed by brittle fracture. Calculations by Zhao et al.[12] demonstrate that the rake angle plays an important role in suppressing and minimizing the anisotropic characteristic.

It can be found that a lot of investigations have been carried out about ultra-precision turning of single-crystal silicon. However, there are few researches about the way of weakening the anisotropy of surface roughness. This study discussed the formation mechanism of surface roughness, etc. Meanwhile, the results are helpful to improve surface quality during ultra-precision turning.

2. Experiments

In order to verify how to improve the uniformity of surface quality, a series of ultra-precision turning experiments was conducted on the (1 1 1) crystal plane.

These experiments were carried out using ultra-precision machine tools developed internally at Harbin Institute of Technology in China, as illustrated in Fig. 1.

The main spindle of the machine tools is powered by an AC servo motor capable of rotating 0–3000 r/min. The self-designed aerostatic spindle has a radial rigidity of 567 N/μm, an axial rigidity of 450 N/μm, and a rotation precision of 0.023 μm. A T-shape layout is employed, with guide rails fitted below the spindle box moving along the z-axis while the tool rest slide moving along the x-axis, which helps to enhance precision. The machine tool body is made from a 2 m × 1.2 m × 0.5 m piece of granite, and is supported by air springs to isolate perpendicular and horizontal low-frequency vibrations, as shown in Fig. 2.

The parameters used in the first series of experiments were: spindle speed = 600 r/min, a_p = 5 μm, and f = 2 μm/r. The diamond tool had an 80 nm edge radius and a −40° rake angle, and the roughness of the machined surface is depicted in Fig. 3.

Assume that the cutting tool on the (1 1 1) crystal plane turns 360° continuously counter-clockwise, and the initial position named as 0° position in the experiment can be set to the [1 1 2] crystallographic direction. Thus, when the cutting tool rotates 30°, 60°, and 90°, the cutting directions are the [1 0 1], [2 1 1], and [1 1 0] crystallographic directions, respectively. Because the properties of single-crystal silicon are periodic,

Fig. 1 Photo of ultra-precision machine tools.

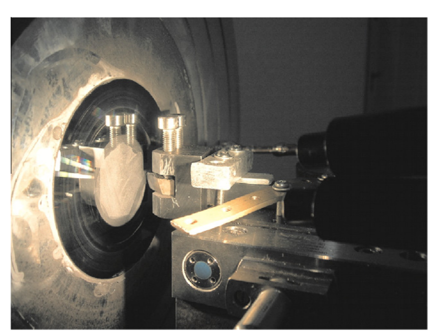

Fig. 2 Photo of experimental setup during machining.