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Full Length Article

Dependence of material removal on crystal orientation of sapphire under cross scratching

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ABSTRACT

The cross scratching experiments were carried out on C- and M-planes of sapphire to investigate the crystal-orientation dependence of crack initiation and damage mechanism. The observed scratching patterns showed that the shallow lateral cracks were dominant along $\left[\bar{1}100\right]$ direction, while both lateral and radial cracks occurred along $\left[01\bar{1}0\right]$ direction on C-plane. However, less surface fractures appeared on M-plane, but with greater scratching affected zone caused by deep lateral cracks in subsurface. The anisotropic scratching patterns were closely related to the activated slip/twinning systems, which accommodate dislocation and provide fracture nucleation during scratching. In addition, the acoustic emission (AE) signals were processed based on Fast Fourier Transform (FFT) and Wavelet Packet Decomposition (WPD), and the results indicate that the anisotropic material deformation under scratching can be identified by the frequency bandwidth and the intensity of special frequency components of the AE signals for the C- and M-planes of sapphire.

1. Introduction

Sapphire is a popular material for Forward Looking Infra-Red (FLIR) windows, domes due to its excellent optical performance and superior mechanical, thermal, chemical stability at high temperatures [1,2]. However, the hexagonal-scalenohedral crystal structure of sapphire results in the anisotropy of material properties along different crystal orientation [3]. This makes it difficult to obtain optical surface of high quality, especially for the aspheric surface with large aperture and steep geometry. Therefore, a further investigation on the deformation mechanisms and fracture behaviors of sapphire along different crystal orientation is a prerequisite for improving the machining efficiency and the surface quality simultaneously.

The diamond indentation and scratching tests are widely used to study the material removal mechanism where the distinct deformation patterns could provide us the primary information on the damage modes involved [4–6]. Different from glasses and polycrystalline ceramics, propagation of cracks in sapphire is mainly along the well-defined crystallographic orientations [7]. As has been reported, Vickers indentation on glass resulted in the formation and propagation of cracks along the corners of indenter where stress concentration appeared, while the dependence of cracks on crystal orientations were remarkable for single-crystal materials [8]. To reveal the deformation mechanisms and fracture behaviors on various sapphire orientations, several investigations have been conducted. Hockey [9] and Chan et al. [10] noted the appearance of basal and rhombohedral twinning, as well as the evidence of several slip systems during the indentation of sapphire. And then the slip and twinning mechanism has been widely studied. Nowak et al. [11,12] summarized the available slip/twinning systems and the relative critical shear stresses (RCSS) for sapphire with an axis ratio of 2.73, which are listed in Table 1. In addition, a new model based on the critical shear stress was developed to discuss the anisotropic surface deformation and fracture of sapphire under indentation, and both the model and indentation tests identified the importance of twinning at the initial stage of the contact-induced deformation for sapphire. Although these indentation studies on sapphire have provided valuable information about the plastic deformation mechanism and the anisotropic incipient fracture, they do not take into account of the dynamic effects on the material removal. The scratching test, regarded as an analogous process of grinding, is a simplified approach to study the material removal mechanism.

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Table 1
The slip/twinning systems and RCSS of sapphire crystal [11].

Symbol	Slip/twinning systems	Description	RCSS
1	$\langle 01\bar{1}1\rangle \left\{01\bar{1}2\right\}$	Rhombohedral twinning	1
2	$\langle 1\bar{1}00\rangle \left\{0001\right\}$	Basal twinning	1
3	$\langle 2\bar{1}\bar{1}0\rangle \left\{01\bar{1}2\right\}$	Rhombohedral slip	33
4	$\langle 2\bar{1}\bar{1}0\rangle \left\{0001\right\}$	Basal slip	103
5	$\langle 10\bar{1}0\rangle \left\{\bar{1}2\bar{1}0\right\}$	Prismatic slip	33
6	$\langle 10\bar{1}0\rangle \left\{\bar{1}012\right\}$	Pyramidal slip	10

Table 2
Properties of sapphire.

Properties	Units	C-planes	M-planes
Melting point	°C	2050	
Usable transmission tange	μm	0.18–5.5	
Knoop hardness [15]	kg/mm^2	1300–1450	1380–1800
Surface energy density [16,17]	J/m^2	>40	7.3
Flexural strength	MPa	1035	1540
Fracture toughness (K_{IC}) [17]	$MPa{\cdot}m^{1/2}$	6.043	2.509
Young's modulus	GPa	456.5	431.2

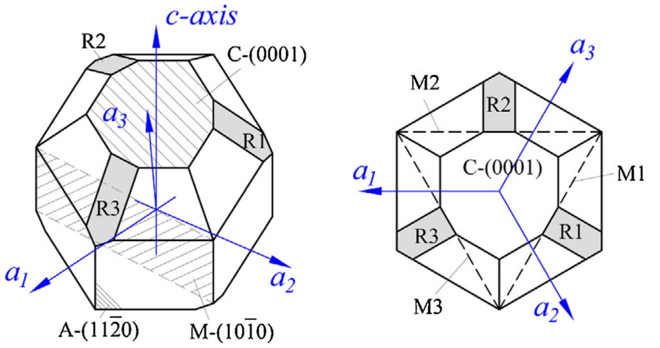

Fig. 1. Coordinate system and sapphire crystal geometry showing the spatial locations of the crystal planes.

Huang et al. [13] have shown that the main deformation mechanism in macro-scale scratching tests is brittle failure due to the limited available slip/twinning systems, and Inkson [14] found that the contact-induced slip and twinning were greatly dependent on the crystallographic orientation of the evaluated surface. It is still of great necessity to investigate the anisotropy behavior of surface patterns under dynamic scratching along various crystal orientation, which contributes to a better understanding of the surface generation and damage mechanism of sapphire.

In the present work, the dependence of the crack initiation and material removal on the crystal orientations of sapphire was investigated by cross scratching experiments. The damage mechanism was studied by analyzing the scratching patterns and characteristics of AE signals along various crystal orientations. Such an understanding is vital to illuminate the fundamental damage mechanisms associated with the crystal orientation and contributes to the development of optical manufacturing technology.

2. Materials and methods

2.1. Material

The commercially available synthetic sapphire (α-Al_2O_3) (Aurora Optoelectronics Co., Ltd. China) was used as the workpiece material to investigate the anisotropic characteristics of material removal under cross scratching. All crystal planes of sapphire are defined relative to the C-plane as it is the plane of physical and optical symmetry. The A-planes and M-planes are all perpendicular to the C-plane, while the R-planes located at 57.6° relative to it, as shown in Fig. 1. For simplicity, the R-planes, including $\left(\bar{1}102\right)$, $\left(0\bar{1}12\right)$ and $\left(10\bar{1}2\right)$, have been marked as R1, R2 and R3, respectively. The M-planes, including $\left(\bar{1}100\right)$, $\left(0\bar{1}10\right)$ and $\left(10\bar{1}0\right)$, have been marked as M1, M2 and M3, respectively. The spatial locations of the investigated surface in this study, the C- and M-planes, were indicated in Fig. 1 by the shaded areas. The mechanical properties for the C- and M-planes are listed in Table 2. The diameter of the sapphire specimens used in the experiments were 25 mm with the thickness of 5 mm. All of them were progressively polished with diamond slurry (9 μm, 3 μm and 1 μm) to remove the original surface defects before the scratching tests. The polished surface was examined by an optical microscope at × 100 magnification.

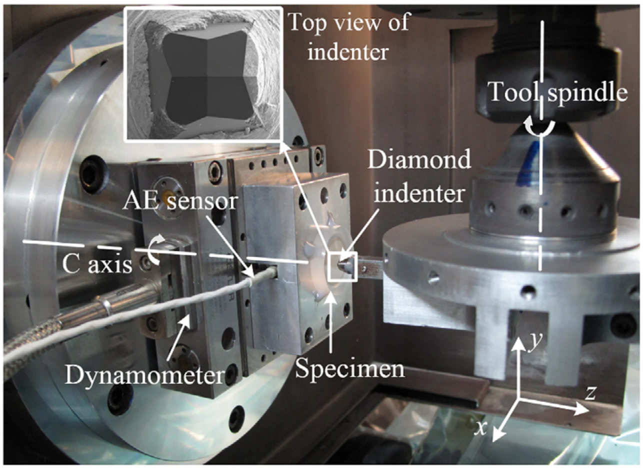

Fig. 2. Cross scratching experimental setup.

Table 3
Cross scratching parameters.

Wheel RPM (rpm)	120
Workpiece RPM (rpm)	2
Depth of cut (μm)	5–6

2.2. Experiments

A Vickers pyramidal indenter was applied as single abrasive grit and cross scratching tests were performed on C- and M-planes of sapphire to evaluate the appearance of surface cracks and study the anisotropy of material removal. Experiments were conducted on an ultra-precision grinding machine. As shown in Fig. 2, the Vickers indenter was rigidly fastened to an arbor and connected to the tool spindle. The AE sensor (Physical Acoustics Corporation) was mounted under the workpiece to detect the tool-workpiece contact for tool setting and signal acquisition, the sampling frequency is 2 MHz. The scratching direction was parallel to one of the indenter diagonals. By controlling the processing parameters, as illustrated in Table 3, a series of non-overlapping scratching grooves along different crystal orientations were performed without coolant addition. The morphology of the scratching grooves was characterized by both optical microscope and scanning electron microscope (SEM).