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Simulation analysis of the effect of tool geometry in diamond turning of KDP crystal

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Abstract
Potassium dihydrogen phosphate (KDP) crystal is one of the most difficult-to-machine optical materials owing to its inherent characteristics of low hardness, high brittleness and easy deliquescence. This paper presents an approach using numerical simulation combined with machining experiment to investigate the effect of tool rake angle on the machining mechanism of KDP crystal. A 3D model with the use of smoothed particle hydrodynamics (SPH) is employed to simulate the diamond turning process of KDP crystal. Simulation results including the stress distribution state and the interface pressure between diamond tool and workpiece are analysed to reveal the underlying mechanism of different tool geometries in machining. Moreover, machining experiments corresponding to the simulation parameters are performed on the tripler plane of KDP crystal. The experiment and simulation results show that the tool with large negative rake angle is conducive to obtaining a crack-free machined surface and suggested for the diamond turning of KDP crystal. It is also proved that the SPH method is a reliable method to investigate the machining mechanism of brittle materials because of the good consistency between experiment and simulation results.

Diamond turning; KDP crystal; Tool geometry; SPH; Machining mechanism

1. Introduction

KDP crystal is a key material for the next generation of laser fusion program, such as the National Ignition Facility (NIF) in the United States [1], the Laser MegaJoule in France [2] and the SG-III laser facility in China. However, it has great difficulty in the precision manufacturing with large size and high surface quality. Traditional processing methods, e.g. grinding and polishing, are not suitable to manufacture such kind of optical materials due to its fragile mechanical and physical properties such as high water solubility, low fracture toughness and sensitivity to temperature change.

Single point diamond turning (SPDT) was firstly employed to machine KDP crystal in 1986 by Fuchs [3]. After that, a lot of work and efforts had been focused on the diamond turning technology of KDP crystal. However, the effect of tool rake angle on the surface generation is still a subject of controversy. Accordingly, this paper aims to investigate the effect of rake angle on the machining mechanism of KDP crystal by using SPH simulation method.

2. Material and Methods

2.1. Material characterization

According to the locations of optics within the laser beamlines, three types of the KDP crystal, i.e. the (001), doubler and tripler plane, are most commonly used. In this work, the selected workpiece is the tripler plane as shown in Fig. 1. As is known to all, the KDP crystal belongs to the tetragonal crystal system, which means that the *z*-axis in Fig. 1(a) is the axis of tetragonal symmetry. The yellow plane in O-x_1y_1 represents the tripler plane which is made into the top surface of the block workpiece during the experiment as shown in Fig. 1(b).

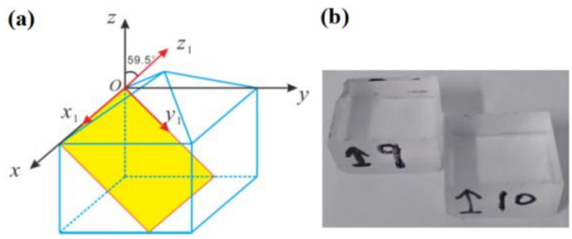

Fig 1. Tripler plane of KDP crystal.

2.2. FE-SPH hybrid model

The finite element method is a very mature technique which has been applied to the simulation of metal cutting processes for a long time. It has fast calculation speed and high efficiency, but it is easily trapped in grid distortion especially when the tool rake angle is negative. Whereas, SPH is a meshfree method that can easily overcome the difficulty of grid distortion. Hence, the FE-SPH hybrid model is established in this work as shown in Fig.2 to take advantage of both approaches.

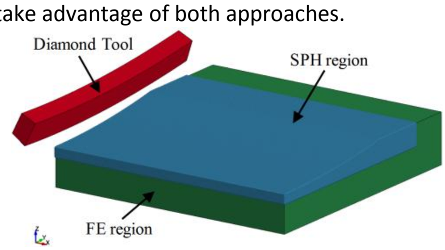

Fig 2. FE-SPH hybrid model.

Red part is the diamond tool that is configured as a rigid body. Due to the inefficiency of SPH method, the nose radius that has small influence on result is set as 0.2 mm to reduce the workpiece size for more efficient simulation. The blue part nearby the tool-workpiece contact area is filled with SPH particles, whereas the green part far from the large deformation area is established by Lagrangian meshes. The full size of workpiece is 60×60×12 μm^3. The depth of cut and feed rate in the simulation are set as 3 μm and 6 μm,respectively. In addition, the material parameters for KDP crystal in simulation are listed in Table 1.

Table 1 Material parameters for KDP crystal

Crystal type	Tripler plane
Density	2.338 g/cm^3
Hardness	2.16 GPa
Young's modulus	53.3 GPa
Poisson rate	0.26
Material model	Piecewise-linear plasticity

3. Results and discussion

The commercial available software LS-DYNA® was employed in this work to simulate the machining process of KDP crystal at different tool rake angles. The hydrostatic pressure that selected to be evaluated in the simulation inhibits the crack propagation, which would reduce not only the number of fracture sites but also increase the size of plastically deformed area [4]. Fig. 3(a) and (b) demonstrate the simulation results of hydrostatic pressure distribution at the tool rake angle of 0° and -25°, respectively. When the tool rake angle is 0°, a large number of dark blue particles under hydrostatic tensile stress spread over the chips and the machined surface. In this condition, the state of high hydrostatic tensile stress would easily cause cracks on the machined surface and make the chips broken and discontinuous. In contrast, when the tool rake angle is -25°, the distribution of hydrostatic pressure is quite different. The number of dark blue particles distributed on the machined surface and chips is decreased significantly, which means that the state of hydrostatic compressive pressure occupies a dominant position in the cutting process at the rake angle of -25°. Thus, few cracks would be left on the machined surface and enhance the surface quality.

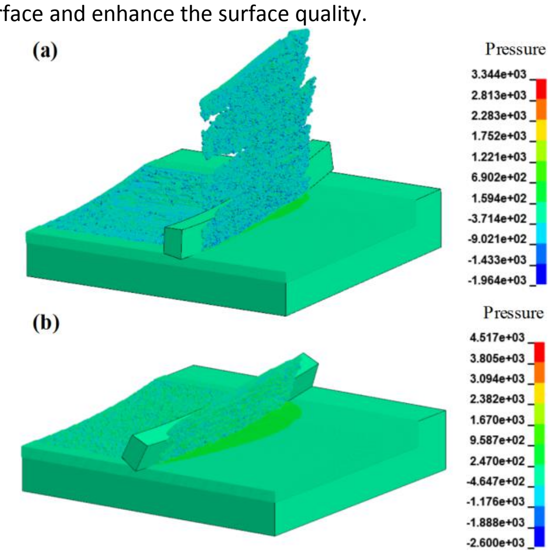

Fig 3. The distribution maps of hydrostatic pressure of various simulations at different tool rake angles: (a) 0°;(b) -25°.

In addition, the distribution of hydrostatic pressure in front of the tool tip is worthy of attention. With the increase of negative rake angle, a large area filled with bright green particles under high hydrostatic compressive stress appears in front of the tool as shown in Fig. 3(b). This would reduce the tendency for fracture to occur and promote the workpiece to be plastically removed. However, a similar area with high hydrostatic pressure can hardly be found in Fig. 3(a) when the tool rake angle is 0°.

In Fig. 4, the interface pressure between tool and workpiece is pictorially presented on the tool rake face. Compared to the tool rake angle of 0°, the interface pressure at the angle of -25° is concentrated near the cutting edge along the tool profile and its maximum is larger. In this condition, the large value of pressure concentrated near the cutting edge is conducive to the inhibition of crack generation and propagation.

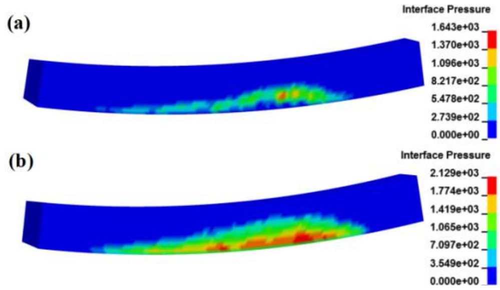

Fig 4. Interface pressure between tool and workpiece at different tool rake angles: (a) 0; (b) -25.

Scratching experiments at different rake angles was performed on the tripler plane of KDP crystal. Fig. 5 presents the results of grooves by using the ultra-depth microscopy. The red arrow is the feed direction of diamond tool with a nose radius of 1 mm. Several cuts were performed one by one from top to bottom as indicated by the black arrows in Fig. 5(a). Obviously, the machined surface and the uncut-shoulder generated by the last cut at the rake angle of -25° is more smooth with very few cracks distributed compared with 0°. As shown in the attached graph in Fig. 5, the surface roughness Ra of 0° and -25° measured by AFM are 26.6 nm and 6.3 nm, respectively. This phenomenon is consistent with the results of simulation analysis. When the large negative rake angle is adopted, the generated high hydrostatic pressure does inhibit the crack initiation and propagation during the processing.

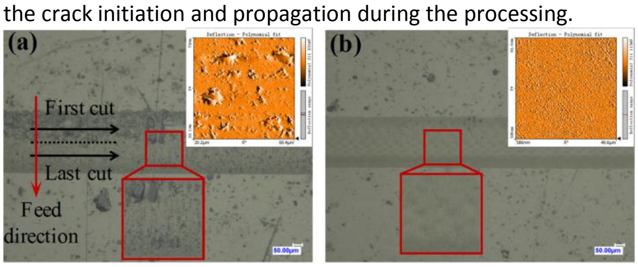

Fig 5. The scratching experiment and measurement in response to different tool rake angles: (a) 0°; (b) -25°.

4. Conclusions

Using the SPH method, it is revealed that the hydrostatic pressure is increased when the tool with large negative rake angle is used. The generation of the high hydrostatic pressure zone in front of tool tip and the large interface pressure near the cutting edge along tool profile are both beneficial to suppress the crack initiation and propagation. Moreover, scratching experiments at different rake angles are performed and the result is in good agreement with simulation analysis, which means that the SPH method is a reliable method to investigate the machining mechanism in diamond turning of KDP crystal and the tool with large negative rake angle is conducive to obtaining a machined surface without cracks.

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