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Experiments on micro-milling of KDP crystal with micro ball-end mills

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Abstract

Potassium dihydrogen phosphate (KH_2PO_4 or KDP) crystal is an optical crystal and it has been widely used as frequency multiplication elements in inertial confinement fusion (ICF) research. Milling of the KDP crystal with a micro ball-end is difficult to achieve high-quality machined surface due to the soft-brittle property of the KDP crystal. The cutting force has been measured in the experiment and the Fast Fourier Transform (FFT) algorithm has been used to filter out the noises in the measured cutting force. The influence of the cutting parameters on the peak-valley value of the cutting force and the surface quality has been investigated. Based on the analysis of the P-V thrust force and the surface roughness *R*a with respect to the cutting parameters, a relatively moderate feed rate and a large spindle speed are recommended for the micro-milling of KDP crystal.

Keywords: KDP crystal, micro milling, cutting force, size effect, Fast Fourier Transform (FFT)

1. Introduction

With its characteristics of being clean, economical and inexhaustible, the nuclear fusion energy has become an ideal energy option for human beings [1]. Potassium dihydrogen phosphate (KH_2PO_4 or KDP) crystal, an optical crystal, has been widely used as frequency multiplication elements in inertial confinement fusion (ICF) project due to its good quality of growth and large electro-optic coefficient [2].

Due to the soft-brittle properties of the KDP crystal, it is prone to generating brittle pits when cutting in the brittle state. Many researches have been carried out on machining the KDP crystal. Tie [3] accomplished the ductile turning of KDP crystal through reasonable control of the cutting parameters and obtained less than 2 nm RMS surface roughness using the fly cutting technique. Wang [4] found that the cutting parameters had big influence on the cutting force using finite element analysis in the turning of KDP crystal.

The previous researches show that the cutting parameters has a great influence on the cutting force and the machined surface quality of KDP crystal in diamond fly cutting and turning. However, there is almost no study in literature on micro-milling of KDP crystal with ball-end mills. Micro-milling experiments of the KDP crystal with ball-end mills have been carried out to study how the cutting parameters influence the cutting force and machined surface quality.

2. Experimental procedure

The micro end milling experiments were carried out on an in-house developed five-axis micro milling tool which is mainly comprised of three linear axes of X, Y, Z, two rotational axes of B, C and a high-speed spindle from NSK®. This NSK® electrical spindle has a maximal rotational speed of 80, 000 r/min and its runout is less than 1 μm. The experimental platform is illustrated in Fig. 1(a).The micro polycrystalline diamond (PCD) ball-end mill with the diameter of 0.5 mm was prepared in-house and was used in the experiments, as shown in Fig.1(b) and (c). The rake angle and relief angle of tool are -50° and 40° respectively. The workpiece material was KDP crystal, and the workpiece dimension was 95 mm × 27 mm × 14 mm.

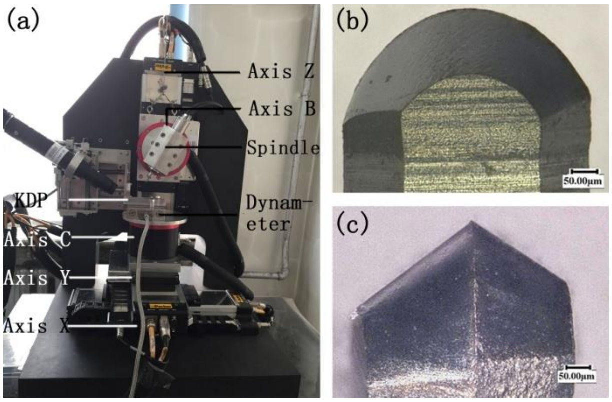

Figure 1. The ultra-precision machine tool system: a) main components, b) and c) side views of micro PCD ball-end mill.

In order to study the effects of the cutting parameters on the cutting force and the machined surface quality, two groups of experiments were conducted by changing spindle speed and feed rate, receptively. The cutting parameters used were shown in Table 1. A dynamometer (Kistler® 9256C2) with a 2mN threshold was used to measure the milling force. The machining forces have been recorded at a sampling frequency of 30,000 Hz. Fast Fourier Transform (FFT) algorithm was used to filter out the noises in the cutting forces.

Table 1. The cutting parameters in the experiments.

Spindle speed *n* (10^4 r/min)	Depth of cut a_p (μm)	Feed rate *f* (μm/z)
3	2	0.2, 0.4, 0.6, 0.8, 1, 1.25, 1.5, 2
6	2	0.2, 0.4, 0.6, 0.8, 1, 1.25, 1.5, 2

The morphology of the workpiece was obtained on a Form Talysurf® PGI 1240 (Taylor Hobson®) and was also used to observe the roughness value *R*a of the micro grooves. For the micro grooves, three different areas have been examined, and the mean and standard deviation of these measured values were taken as the surface roughness *R*a of the machined grooves and the measurement error, respectively.

3. Results and discussion

3.1. FFT analysis of the signals of cutting force

In the micro milling of KDP crystal, the cutting force should have a certain periodicity because the cutting thickness in the following cutting cycles is same as that in the current cutting cycle when the cutting parameters are fixed. The three-dimensional cutting force was measured by the dynamometer under the cutting parameters, namely the feed rate of 1 μm/z, depth-of-cut(DoC) of 2 μm and the spindle speed of 6×10^4 r/min. The FFT was carried out to filter out the noises. The comparison in terms of original thrust force and the force after FFT filtering were performed as depicted in Fig. 2. The magnitude of the thrust forces after FFT filtering was a bit smaller than the original emission signals. The cutting force after FFT filtering has a regular periodicity and matches well with the original thrust force which would represent the original thrust force well.

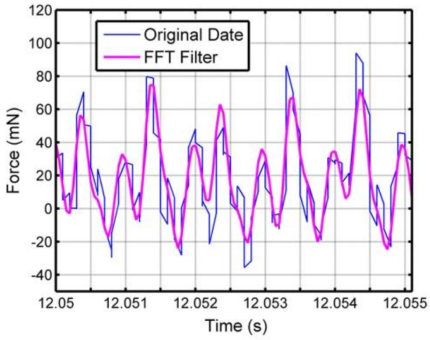

Figure 2. Comparative curves between original cutting force and force after FFT filtering.

3.2.Effects of cutting parameters on cutting force and surface roughness Ra

The peak-valley (P-V) value is one of the commonly used parameters for estimating a quasi-dynamic component of the cutting force, and it is referred to the amplitude between the maximum and the minimum values within a spindle revolution. In order to obtain an overall perspective of the effect of the cutting parameters on the cutting forces, the P-V values of the cutting forces were analysed and averaged over 100 revolutions. In this study, only the P-V thrust force was studied because it has the largest influence on the machined surface quality [5].

Generally, the P-V value of the thrust force increased as the feed speed augmented for both spindle speed, as shown in Fig. 3 (a). When feed rate is around 0.5μm/z, the P-V value of the thrust force reached a local minimal value at both spindle speeds. The reason may be that the size effect of the cutting edge radius occurs around 0.5μm/z. When the feed rate is below the feed rate zone of around 0.5μm/z, chips are not generated at the first tool pass and the ploughing effect occurs. Once the feed date is above this threshold, chips are generated and the P-V value of cutting force increases, which is caused by the increase of the cutting thickness in the cutting edge's radial direction as the feed speed augmented.

The roughness value Ra of the micro grooves was measured and the results are shown in Fig. 3 (b). It can be clearly seen that the change of the roughness value was similar to the P-V value of the thrust force, which indicates that the cutting force could predict the surface quality indirectly. From these experiments results, a relatively moderate feed speed is recommended in the micro-milling of KDP crystal, because the roughness *R*a becomes larger when the feed rate is smaller than a certain value, while a relatively large spindle speed is also recommended because the roughness *R*a is larger at a smaller spindle speed of 3×10^4 r/min.

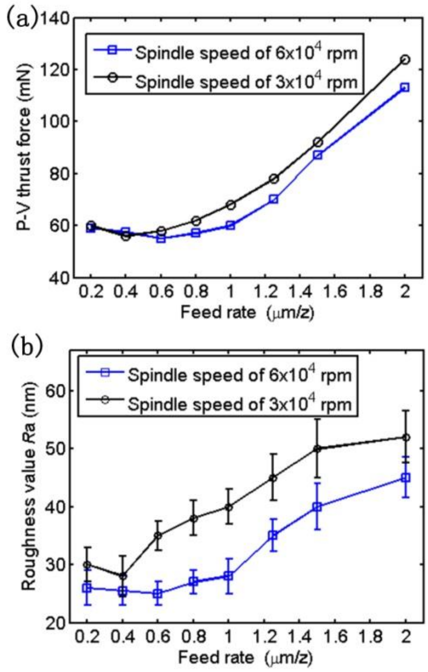

Figure 3. Influence of feed rate on P-V thrust force and roughness *R*a.

4. Conclusions

Micro milling experiments with ball-end mill have been carried out and the cutting force has been also measured. FFT has been used to filter out the noises in the cutting forces which has proven to be a good method. By analysing the change of the P-V thrust force and the roughness *R*a along with the cutting parameters, a relatively moderate feed rate and a large spindle speed are recommended in micro-milling of the KDP crystal. Further on-going research is to study the size effect in micro milling KDP crystal when the cutting thickness is around the cutting edge radius.

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