Effect of cutting speed on the material removal behaviour for sapphire

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Abstract. Sapphire optical components are widely used in various industrial sectors. However, they are currently not available through efficient and highly accurate ultra-precision cutting. Therefore, this paper investigates the effect of cutting speed, a key factor in ultra-precision cutting, on the removal behaviour of sapphire materials. The plunge-cuts tests at different cutting speeds (10, 20 and 30 mm/s) have been conducted. The groove surface morphology, critical cutting depth for ductile-brittle transition, cutting force and tool wear of each plunge-cuts test with various cutting speed test were analysed. The experimental results shown that increasing the cutting speed is beneficial to obtain less defective machined surfaces and increase the critical cutting depth for ductile-brittle transition. However, at the same time, the cutting force increases dramatically in the brittle removal mode during high-speed cutting, which leads to severe tool wear. Therefore, increasing the cutting speed to meet the requirements of ultra-precision cutting and machining within the critical cutting depth is a highly efficient measure for obtaining sapphire optical surfaces.

1 Introduction

Sapphire is a high-performance engineering material and its optical components are widely used in aerospace, communications and semiconductor fields, offering unique mechanical, chemical, thermal, and optical properties [1,2]. These applications require for high quality surface finish, dimensional and form accuracy, which are commonly achieved through ultra-precision grinding [3]. However, the efficiency of ultra-precision grinding is low and it is difficult to meet the increasing demand of sapphire components. Therefore, it is urgent to explore a new machining method that can realize the ductile regime cutting of sapphire.

Ultra-precision cutting technology with high machining accuracy and efficiency is an ideal method to fabricate sapphire optical components. At present, the research of sapphire ultra-precision cutting mechanism is still blank. In previous studies, Min et al. found that ductile domain removal could be achieved in sapphire plunge-cut tests [4, 5]. Therefore, the strategy of obtaining sapphire optical element by cutting is feasible. It is well known that the cutting speed is crucial to the quality of the machined surface [6]. Thus, it is important for

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realizing ultra-precision cutting of sapphire to obtain insight into the characteristics of material removal behaviour with different cutting speeds.

This paper aims to reveal the effect of cutting speed on the removal behaviour of sapphire material. To achieve this objective, the plunge-cuts tests at different cutting speeds (10, 20 and 30 mm/s) have been conducted. The groove surface morphology, critical cutting depth for ductile-brittle transition (DBT), cutting force and tool wear of each plunge-cuts test with various cutting speed test were analysed. The effect of cutting speeds on material removal mechanism of sapphire is discussed based on the experimental results.

2 Experimental procedure and simulation

2.1 Materials and Vickers indentation tests

The specimen was commercially acquired and its shape was a cylinder with a diameter of 20 mm and a length of 3 mm. Before the scratching testing, the end face of the cylinder, the C plane, was polished to roughness Sa less than 0.2 nm.

The plunge-cuts tests were performed along $[10\bar{1}0]$ direction on the *C* plane. The ultra-precision lathe (Nanotech 450 UPL, Moore, USA) was employed to conduct the plunge-cuts tests as shown in Fig. 1. The cutting force was measured by a dynamometer (9119AA2, Kistler, Switzerland). Tool wear and the groove topography were detected by a metallurgical microscope (DM2700M, Leica, Germany).

As displayed in Fig. 1(a), the sapphire substrate was cut under orthogonal cutting conditions with a cutting slope of 0.0573° by an NPD (nano-polycrystalline diamond) tool. The NPD tool geometry included the corner radius of 0.8 mm, the rake angle of -20°, and the relief angle of 8°. The feed speeds were 10, 20 and 30 mm/min, respectively.

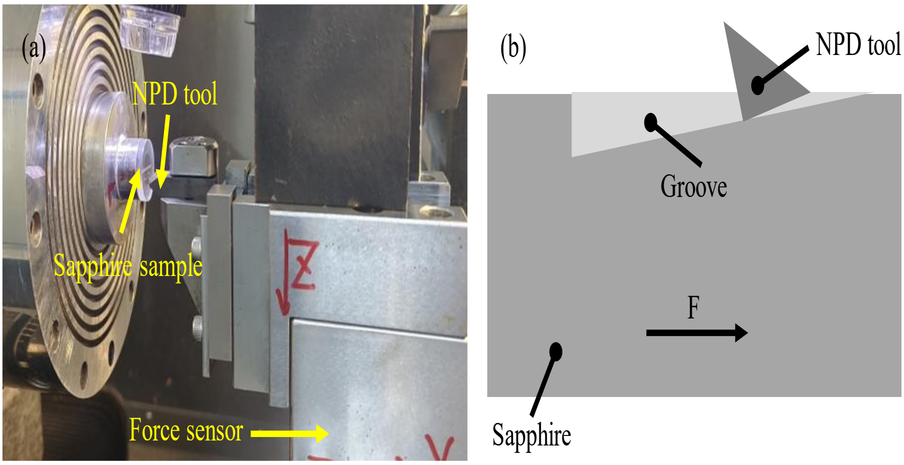

Fig.1. (a) Experimental setup of plunge-cuts tests, (b) Schematic experimental procedure of plunge-cuts.

3 Results and discussion

3.1 Grooves topography and critical cutting depth for DBT

The groove topography at different cutting speeds was shown in Fig. 2. Three distinct removal regimes, namely, ductile regime (DR), ductile-brittle transition regime (DBTR) and brittle regime (BR) were observed at each groove. In addition, significant spalling was observed in the groove cut at 10 mm/s. With the increase of cutting speed, pits became the main defect form instead of spalling, and the pits were distributed in an arc. It indicated that the change of cutting speed led to different brittle failure modes during processing.

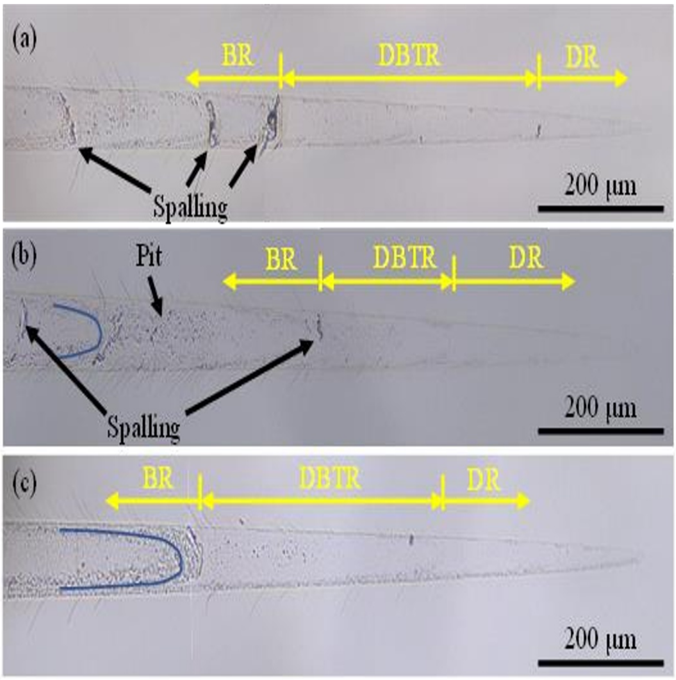

Fig. 2. The topography of grooves cut at (a) 10 mm/s, (b) 20 mm/s and (c) 30 mm/s.

The critical cutting depth for ductile-brittle transition is defined as d_c which characterizes the possibility of high quality of machining surface in cutting process [7]. The d_c is represented by the Eq (1).

$$d_c = R - \sqrt{R^2 - (L/2)^2} \tag{1}$$

Where R denotes the corner radius of the NPD tool and L represents the width of the end position of the DR. The d_c values for each groove of different cutting speeds were shown in Fig. 3. It can be seen that increased significantly with the increase of cutting speed. This work implied that increasing the cutting speed was conducive to obtaining a high-quality machined surface in the process of ultra-precision cutting sapphire.

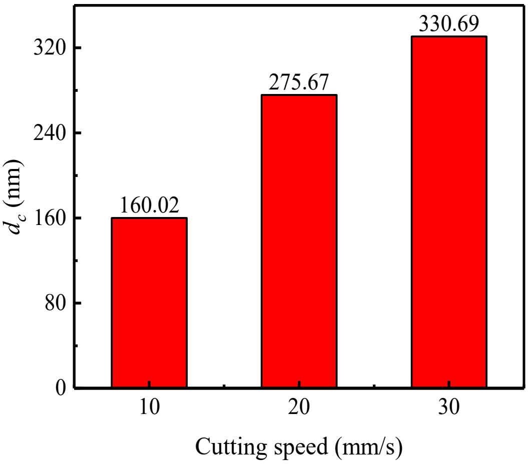

Fig. 3. The d_c values for each groove of different cutting speeds.

3.2 Cutting force

Cutting force is an important factor in obtaining high quality surfaces [8]. And it can directly reflect the material removal mode in the cutting process. In order to improve the anti-interference and signal-to-noise ratio of cutting force signal, the signal with frequency less than 20 Hz was filtered out. The cutting forces at different cutting speeds were shown in Fig. 4, which increased as the cutting speed increased. In addition, all cutting forces at the three cutting speeds initially increased steadily, and no obvious bounce was observed, which corresponded to the DR of the sapphire groove. As the cutting depth increased, the cutting force showed slight fluctuations, indicating that the material removal mode was the DBTR, resulting in pit damage on the groove surface. Finally, the sharp oscillation of cutting force was caused by the large area of sapphire spalling, which meant that this stage was the BR. Based on the above analysis, the cutting force signals were divided into three regions as shown in Fig. 4. The cutting distances corresponding to the cutting forces in the DBTR and DR stages in Fig. 4 are generally consistent with the lengths of the corresponding regions in Fig. 2. However, the cutting distance corresponding to the cutting force in the BR stage is significantly more than the length of BR in Fig. 2. This is attributed to the fact that the machining marks at lower cutting depths are unable to remain on the sapphire surface due to its elastic recovery. Thus, cutting force analysis can be employed to characterize material removal mode as well as machined surface quality during the cutting process.

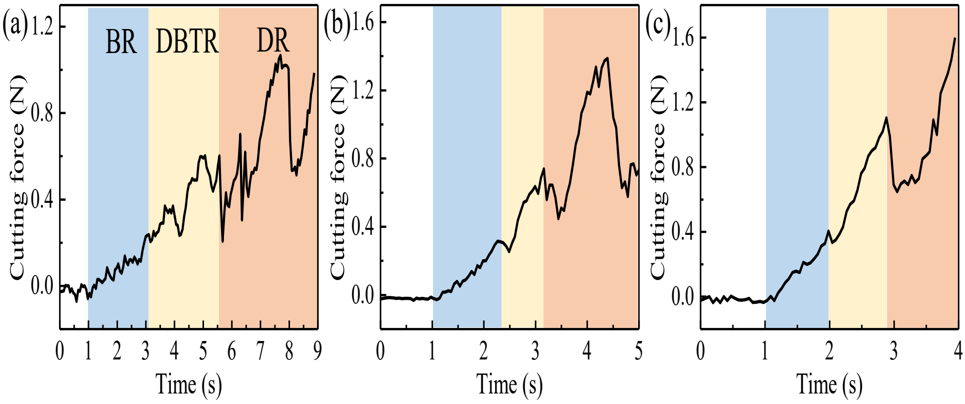

Fig. 4. Cutting forces of three cutting speeds at different times.

3.3 Tool wear

The tool plays an important role in cutting and is closely related to the machining quality [9]. Therefore, it is necessary to pay attention to the tool wear during cutting. The tool wear after finishing the micro groove cutting was shown in the Fig. 5. Micro-chipping was observed on all three cutting tools. Among them, the most severe tool wear after cutting at 30 mm/s was due to the catastrophic cutting force on the cutting edge during the brittle material removal stage of the cutting process. In addition, the DR range of the grooves cut at 30 mm/s was significantly larger than the others, which also indicated that the micro chipping of the tool is developed at the brittle material removal stage at the end of the cutting process. It can be concluded that increasing the cutting speed would not lead to serious damage to the tool during the ductile removal mode of the sapphire material.

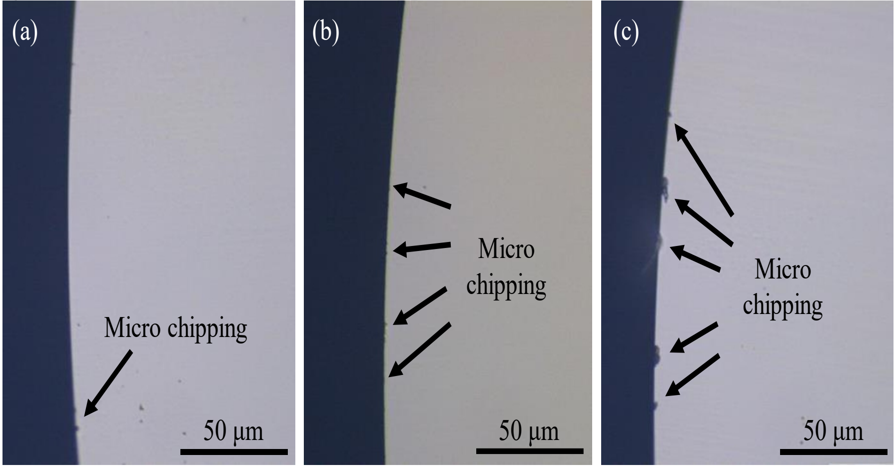

Fig. 5. Tool wear. (a) 10 mm/s, (b) 20 mm/s and (c) 30 mm/s

4 Conclusion

In present work, the effect of cutting speeds on material removal behaviors in terms of groove surface morphology, critical cutting depth for ductile-brittle transition, cutting force and tool wear in sapphire cutting process were studied. The following conclusions were obtained:

(1) With the increase of cutting speed, the surface damage of the groove is reduced and the critical cutting depth for ductile-brittle transition is increased.
(2) The cutting force was positively correlated with the cutting speed, and the material removal mode can be identified according to the vibration characteristics of the cutting force.
(3) Tool wear deterioration with the increasing cutting speed due to sharp increase in cutting forces during the brittle material removal stage.

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