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Understanding of Residual Stress and Subsurface Damage by 2-Step Machining of Single Crystal Sapphire

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Abstract: Machining is in general conducted in multiple paths and thus residual stress and subsurface damage formed by previous cut may influence subsequent cutting. Ceramics materials are extremely brittle and prone to cracks. Ultra-precision machining with very small depth of cut enables ductile mode cutting. There have been various reports that critical depth of cut (CDC) for single crystal sapphire exists, where the ductile to brittle transition occurs. However, the CDC of subsequent cutting changes due to the influence of residual stress and subsurface damage by previous cut. This study investigates the indirect effect of residual stress and subsurface damage on the critical depth of cut of the second cut by analyzing the plastic deformation mechanisms activated during 2-step machining on A-plane of sapphire. It was found that the $[\bar{1}100]$ machining orientation was most suitable since the critical depth of cut remained fairly constant due to dominant rhombohedral twinning activation during subsequent machining operations.

Key words: residual stress, ultra-precision machining, sapphire

1. Introduction

As the performance boundaries are constantly pushed across various fields, the need for materials that can withstand challenging environments is ever increasing. Single crystalline sapphire is a potential material of choice for such applications due to superior mechanical properties, high temperature resistance and chemical inertness. In spite of possessing many favorable properties, fabricating required geometries from sapphire through machining processes is a challenge due to high hardness, anisotropic properties, and brittleness [1)].

Ultra-precision machining (UPM) is one of the approaches that allows for fabrication of complex geometries in single crystalline ceramic materials by taking advantage of the ductile-brittle transition (DBT) observed at the sub-micron scale. However, during the machining process for most components, multiple passes over the same region of the workpiece are necessary to get from the raw material to the finished product. During these repeated cutting events, residual stresses and subsurface damage accumulate with each machining step leading to brittle fracture at premature stresses which can hinder the functionality of the machined part [1), 2)]. Removal of surface cracks and minimizing residual stresses require extensive post processing which can significantly add to the cost of the part.

In this study, the effect of cutting orientation and machining depth on the critical depth of cut (CDC), the depth at which ductile-brittle transition occurs, during 2-step machining is investigated from a crystal deformation perspective on A-plane of sapphire. The results provide some insights into suitable machining strategies to improve the machining throughput while minimizing subsurface damage and residual stress.

2. Predicting Plastic Deformation and Fracture Mechanisms During Machining of Ceramics

In single crystalline materials, if the orientation of the crystal and, the magnitude and direction of applied load are known, the likelihood of activation of specific slip/twinning and fracture mechanisms can be predicted by extending the Schmid law. In the case of machining, the direction and magnitude of cutting and thrust forces are measured using a dynamometer and the resultant force is used for the analysis. The likelihood of activation of a given slip/twinning mechanism is given by Eq. (1).

$$P_i' = m_i'/(\tau_i^{crit}/min_i\ \tau_i^{crit}) \tag{1}$$

Where P_i' is the tendency of activation of the i^{th} slip/twinning system, m_i' is the modified Schmid factor, τ_i^{crit} is the critical resolved shear stress of the i^{th} slip or twinning system. In certain cases where multiple plastic deformation mechanisms have a similar probability of activation, dislocation entanglement can arise which can lead to easy crack initiation. Further details on the analysis methodology can be found in work by Kwon, et al. [2)].

3. Experimental Setup

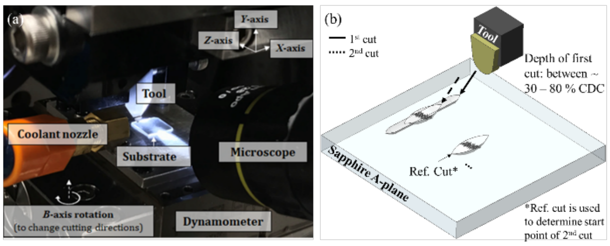

Fig. 1. (a) Experimental setup, (b) Schematic of 2-step machining experiment performed on A-plane of sapphire.

2-step cutting experiments were carried out on the A-plane of sapphire using a 5-axis ultra-precision machine tool (FANUC ROBONANO α-0*i*B) using a BL-PCD tool (A.L.M.T. Corp.) with a 0.5 mm nose radius (Fig 1.(a)). The cutting speed chosen was 5 mm/min and cutting was performed in the 0° $[0001]$, 60° $[\bar{1}012]$, and 90° $[\bar{1}100]$ orientations. The depth of cut of the first cut was varied between 30 – 80% of the CDC for the given cutting direction and a second cut (plunge cut) with an entrance and exit slope of 1/500 having a maximum depth of cut of 600 nm was performed over the previously machined first cut (Fig 1.(b)). A reference cut, offset from the second cut by 150 μm was machined to help determine the start point of the first cut. The cutting forces were recorded using a piezoelectric dynamometer (Type 9119AA1, Kistler Corp.) and CDC was determined using optical images (VHX 5000, Keyence Corp.). Further details regarding the experiment have been documented in our previous work [2)].

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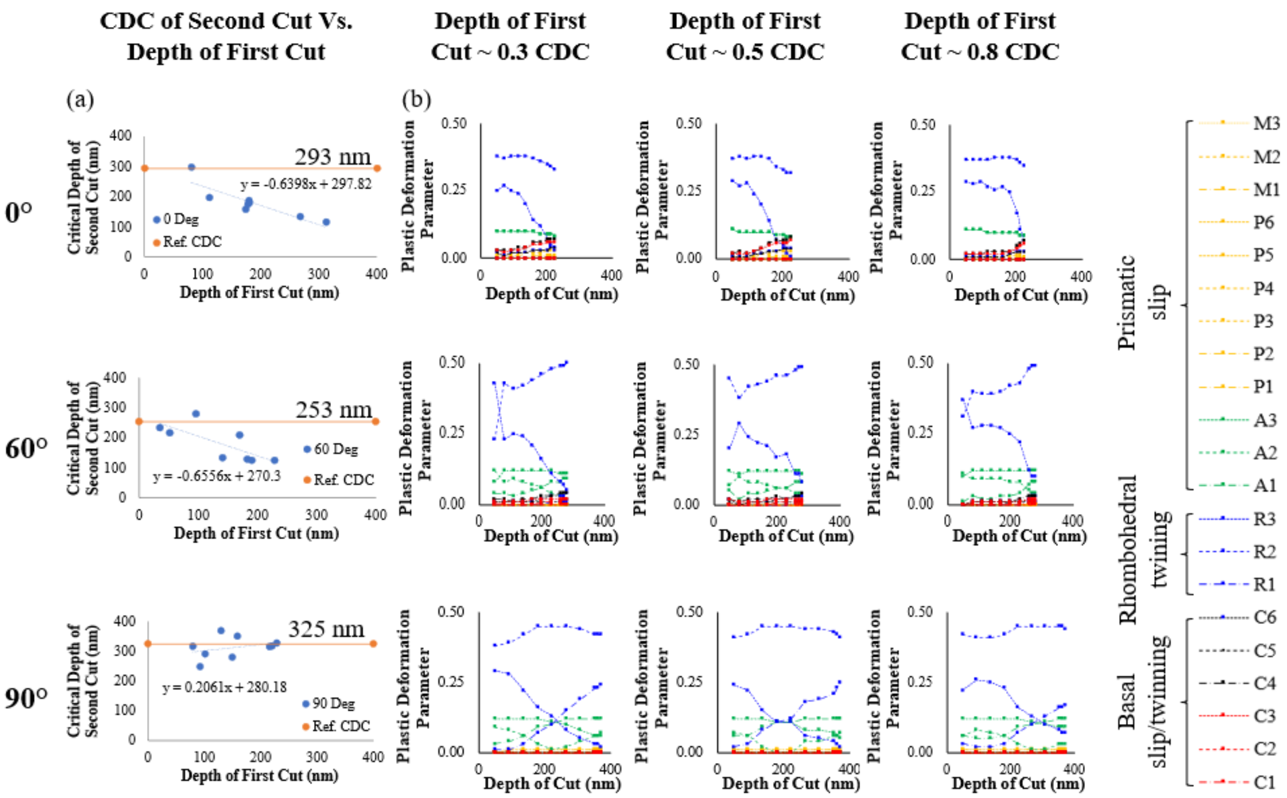

Fig. 2. (a) Variation in CDC of second cut as a function of depth of first cut for 3 cutting orientations on A-plane of sapphire [3], (b) Plastic deformation parameter as a function of depth of cut of second cut for 3 representative cases (0.3, 0.5, 0.8 x CDC).

4. Results and Discussion

4.1 CDC of Second Cut

In the case of 0° and 60° machining orientations, as the depth of first cut is increased, the critical depth of the second cut decreased (Fig. 2.(a)). This implies that as the depth of the first cut increases, residual stresses and subsurface damage build up which initiates cracks at a premature load during the subsequent machining operation. However, in the case of 90° cutting orientation, the CDC of the second cut remained fairly consistent as the depth of first cut was increased. This result implies that in the case of 90° cutting orientation, either the subsurface damage and residual stresses are very low or an interaction between multiple deformation mechanisms could be acting complementary to each other which suppresses crack initiation.

4.2 Analysis of Plastic Deformation During the Second Cut

In order to better understand the differences in the CDC of the second cut for different cutting directions, the tendency of activation of different plastic deformation mechanisms were calculated using the methodology described in section 2 (Fig 2.(b)). In all the cases, rhombohedral twinning (R2, R3) was observed to be the dominant plastic deformation mechanism. However, the relative likelihood and variation with respect to depth of cut of the second cut were different for each of the cases which could possibly explain the reason for the trends observed in Fig 2.(a).

In the case of 0° and 60° machining orientations, the tendency of activation of R2 and R3 twinning are fairly similar at lower depths of cut which could lead to both the mechanisms getting activated leading to dislocation pile ups which are potential sites for crack initiation. In the case of 90° orientation, the tendency of activation of R3 twinning rapidly decreases which leaves behind only one dominant mechanism driving plastic deformation (R2 twinning). As a result, not much subsurface damage or residual stress accumulates in this cutting direction thus maintaining a constant CDC during subsequent machining.

5. Conclusions

During the 2-step machining experiments performed on A-plane of sapphire, it was observed that 90° cutting orientation is most favorable to subsequent machining operations as a fairly constant CDC can be maintained even with a large depth of cut of the first pass due to lower accumulation of subsurface damage and residual stresses. In future work, TEM samples for various cases will be investigated in order to better understand subsurface damage formation.

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