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A study of the performance of cutting polycrystalline Al 6061 T6 with single crystalline diamond micro-tools

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ABSTRACT

A study was carried out to understand the mechanism of cutting polycrystalline Al 6061 T6 with single crystalline diamond (SCD) micro-tools using a 5-axis ultra-precision machine. The crystallographic structure, such as grain size and grain orientation, was found to play a significant role on the cutting performance. Variations in cutting force, chip formation and machined surface finish were observed as a result of changes in crystallographic structure. The hard and brittle micro-particles were found embedded in the metal matrix of Al 6061 T6. Cracks generated in the hard particles could be observed on the machined surface after the hard particles were brittle-mode cut by a micro-tool at a coarse cross-feed. These cracks also lead to surface imperfections such as voids or scratched lines on the machined surface. Cutting strategies of reduced cross-feed and/or applying ultrasonic vibration on the micro-tool tip were demonstrated to achieve a stable-state cutting performance with constant cutting force, an improved roughness of the machined surface finish and reduced burr size. High aspect ratio micro-pillar arrays with individual pillar size down to $\sim 1.1 \times \sim 1.3 \times \sim 5.3$ (height) μm have been generated employing the cutting strategies.

1. Introduction

Polycrystalline Al alloy 6061 T6 is a widely used material for ultraprecision components because it is thermally stable, has high strength and light weight, and can be cut with diamond tools to produce optical quality surfaces. In recent years, mechanical machining of micro-features/parts of such polycrystalline engineering materials, has become an emerging and challenging research area because the mechanism of machining on the micro-scale is different from that of conventional machining. It was reported that crystallographic structure such as grain orientation or/and grain size play a significant role in the performance of machining such alloy or Al single crystal [1–7]. Ding et al. [7,8] have reported that 2nd phase hard and brittle micro-particles embedded in the matrix of Al 6061 T6 lead to the prevalence of voids/scratched lines and consequent degradation of the surface finish during either single point diamond turning or cutting with micro-tools at a coarse cutting feed rate. In this paper, a study was carried out to further investigate both effects of the crystallographic structure and hard particles on the performance of cutting this material with single crystal diamond (SCD) micro-tools, leading to proposing a strategy that is expected to improve the cutting performance with micro-tools.

2. Cutting experiments

All cutting experiments were conducted using a Moore Nanotech 350 ultra-precision Freeform Generator. A Kistler dynamometer (9256C1 Minidyn Multicomponent Dynamometer) was used to detect the forces during cutting. A Wyko NT3300 optical profiler was used to measure the depth and width of the machined groove, machined surface finish and pillar size.

A FEI dual beam focused ion beam (FIB) system (Nova Navolab) was used to fabricate the SCD micro-tools and obtain micrographs of the machined workpieces from scanning electron microscope (SEM) imaging. Due to the dependence of ion beam channeling effects on crystal orientation, crystallographic structure of different orientations could be clearly seen from scanning ion microscope (SIM) imaging [9]. A typical crystallographic structure of Al 6061 T6 after FIB etching is shown in Fig. 1. The grain size ranged from a few micrometers to 50 μm. Compositions and properties of Al 6061 T6 are given in [7,8].

Two types of SCD micro-tools were used in this study: those that were produced with FIB sputtering [10] and those that were

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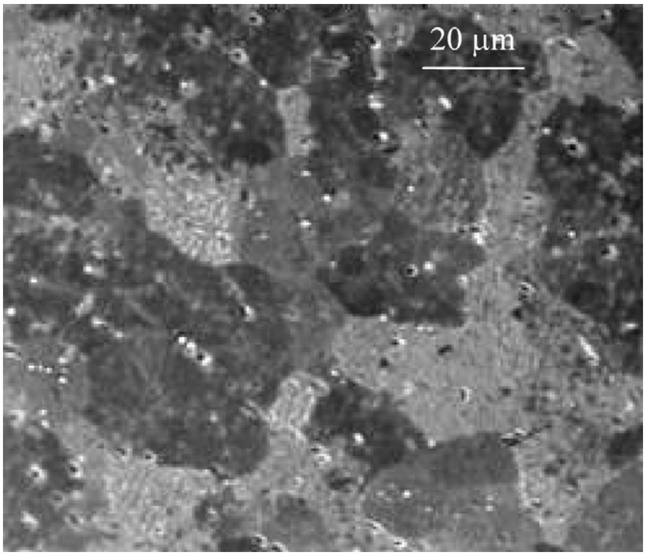

Fig. 1. Crystallographic structure of Al 6061 T6 (after FIB etching).

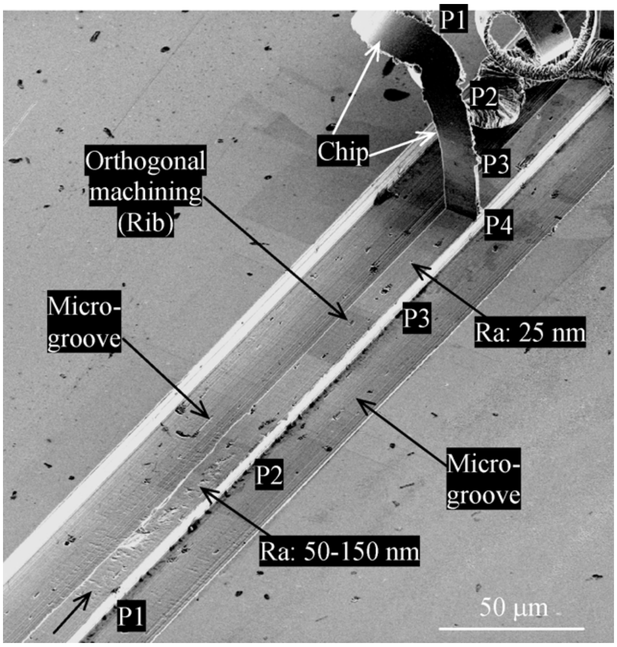

Fig. 3. Chip generated in orthogonal machining of Al 6061 T6. Cutting depth: 0.8 μm. The orthogonal micro-machining stopped at P4. Arrow without label shows the cutting direction (Materials' locations from P1 to P3 on the chip sequentially removed at P1 to P3 on the top surface of the rib. FIB fabricated micro-tool).

purchased commercially. The rake angle of FIB-sputtered tools was 0 ± 1.5° and both primary and side clearance angles were 7° ± 1.5°. The tool had an Ra better than 40 nm on all tool facets. The tool edge radius was in the range of 15–18 nm [10]. For the commercial tools, the rake angle, the primary clearance angle and side clearance angle were 0 ± 0.5°, 7 ± 1.0°, and 1 ± 1.0°, respectively, and with an Ra better than 10 nm on all tool facets. The tool supplier claimed that the tool edge radius was less than 100 nm. The cutting contact length at the primary clearance face was around 30 μm for both types of tools.

Before the cutting tests with micro-tools, a conventional SCD tool with a nose radius of 0.5 mm was used to shape the top surface of the work material with the same ultraprecision machine in order to ensure its flatness. Sufficient coolant was applied during the shaping process. After surface shaping, two cutting setups were carried out to study the cutting mechanism with SCD micro-tools: orthogonal cutting and micro-grooving. Orthogonal cutting was performed on the top surface of the rib formed by two micro-grooves as shown in Fig. 2(a). The width of the rib was around 10 μm which was smaller than the cutting contact length of around 30 μm at the primary clearance face of the micro-tool. Micro-grooving was performed on the shaped surface as shown in Fig. 2(b). The width of the chip (cutting contact length at the interface between the chip and the rake face) was equal to the length of the cutting edge at the primary clearance face of the micro-tool (around 30 μm). The depth of micro-groove is approximately equal to the cutting depth. The detailed descriptions of both cutting setups were reported in [11]. The micro-tool was carefully aligned to an accuracy of better than 0.1° between the cutting edge on the primary clearance face and the top shaped surface of the workpiece. Moreover, experiments could be carried with a cutting depth tolerance of 0.05 μm [7]. In this study, a slow cutting speed of 1 mm/min was employed due to the grain size of the material for the purpose of properly measuring the cutting forces with high accuracy and high resolution.

3. Results

3.1. Orthogonal cutting experiments

Orthogonal cutting (Fig. 2a) was carried out using a FIB sputtered SCD micro-tool at a cutting depth of 0.8 μm and a cutting speed of 1 mm/min, without the use of coolant. Fig. 3 shows that a chip was

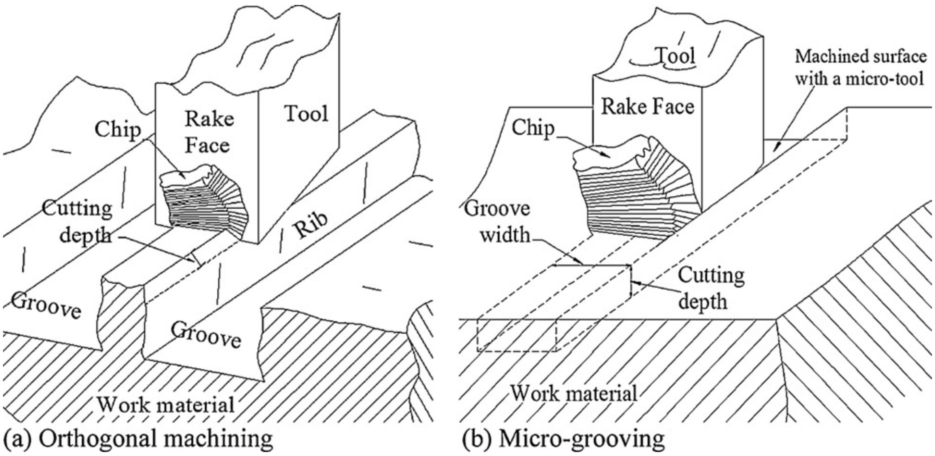

Fig. 2. Schematic of orthogonal cutting and micro-grooving with a micro-tool [11].