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Variation in Machinability of Single Crystal Materials in Micromachining

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Abstract
For practical application of micromechanical machining, four levels of process realization are required; fundamental understanding of process physics, development of microplanning (processing parameter optimization), macroplanning (tool path planning), and design optimization. This study surveyed the influence of localized variation in the microstructure on final process outcome and machinability of brittle optical material in a ductile regime. A clear correlation between burr height, critical depth of cut and crystallographic orientation was found on single crystal materials (copper and magnesium fluoride), giving insight into optimal orientations and process parameters for acceptable micromachining process outcome.

Keywords:
Micromachining, Burr, Single crystal

1 INTRODUCTION

Current demands in the manufacturing sector, particularly with the ever-present need for miniaturization of components in everyday products such as consumer electronics, etc., have predicated the need for processes that can generate smaller features with a reliable and suitable degree of precision, particularly at the mesoscale (sub-millimeter level) and microscale (micron-level). Scaled-down versions of traditional mechanical manufacturing processes such as drilling and milling may serve as viable complementary processes to fabrication techniques such as MEMS for feature generation at the meso- and microscale. However, many challenges remain for such micromechanical machining processes (hereafter referred to as "micromachining") to be implemented at the production level. One particular challenge is to fully understand and characterize the nature of process-induced defects in micromachining, surface and edge finish in particular, in order to better understand how to create more efficient process-plans for optimal manufacturing throughput and quality.

Previous work done by Ueda et. al. demonstrated a significant variation in cutting force and chip topology in microcutting of brass as a function of crystallographic orientation [1]. Subsequent work by Sato et. al. also indicated a significant variation in surface finish, chip topology, and cutting force during machining of single crystal aluminum [2]. Similar work by Yuan et. al. has demonstrated variation in surface finish and cutting force in continuous face turning of single crystal copper [3], and work done by the authors has demonstrated a significant change in chip morphology and surface/edge condition in microdrilling and ultraprecision flycutting [4], and in ultraprecision machining of single crystal copper [5]. Brinksmeier et. al. investigated tool wear in ultra-precision machining [6] and Uhlmann et. al. studied dynamic analysis for micro-end mill optimization [7]. However, the majority of current micromachining research has focused on fundamental understanding of the effect of workpiece microstructure on process outcome, but without much focus on results for applications. In order for micromachining to be practical for production-level manufacturing of optical devices, micromolds, and bio-medical devices, strategic process planning utilizing the aforementioned understanding is critical. Here, four levels of process planning for micromachining are suggested.

- Understanding of process physics
- Micro process planning (processing parameter optimization)
- Macro process planning (tool path planning, etc.)
- Design optimization

In order to accumulate the knowledgebase for these four levels of process planning, a collaborative research team from University of California at Berkeley, U.S.A., Keio University and RIKEN, Japan focuses on edge and surface finish in two distinctive materials; OFHC copper (FCC crystal structure), which is used for electrical components, and MgF_2 (tetragonal structure), which is widely used for infrared and ultraviolet range optical devices and as windows for excimer lasers. With ever-increasing demands for optical components with complex geometries, such as aspherical/Fresnel lenses and diffraction gratings, greater understanding of the fundamental material removal mechanism is required to generate these features with the required degree of precision.

The experiments on OFHC copper focuses on edge effects because for such devices, edge finish is very important, and experiments on MgF_2 focus on the generation of smooth surfaces via ductile-mode machining for optical requirements.

When cutting single crystal materials at the precision scale, the specific orientation of the material with respect to the cutting direction will have a significant impact on the resulting surface and edge condition. Therefore, unlike conventional metal cutting, the cutting mechanism in ultraprecision machining is more influenced by the crystallography and active dislocation slip systems within the workpiece. An example of this is shown in Figure 1, which shows the relative orientations of the crystallographic planes in a face-centered-cubic (FCC) single crystal material with respect to a theoretically-small micromilled trench (it is important to note that there is no existing micromachining technology as of yet that can machine such a feature). FCC materials typically have four slip planes (the family of (111) planes) and three slip directions (the family of [110] directions), leaving a total of 12 possible slip systems for dislocation movement to take place. As a micromachining tool sweeps across the surface of the machined surface, the tool path constantly changes orientation with respect to the workpiece, leading to different crystallographic slip systems being activated, and a different resultant surface and edge condition.

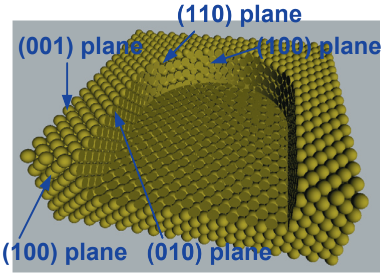

Figure 1: Relative orientation of crystallographic planes in theoretical micromachine trench.

In addition, the machining of normally brittle materials (such as many optic glasses, ceramics, etc.) is highly desirable over conventional techniques (such as traditional polishing) due to increased flexibility in geometries produced, and higher material removal rate, translating to higher production throughput. However, while machining brittle materials in conventional machining tends to cause excessive surface and subsurface cracking, machining in a ductile mode at a low enough depth-of-cut (DOC) has been proposed by many researchers, including Bifano [8]. While this topic has been studied in depth for polycrystalline brittle materials, the machining of single crystal brittle materials in a ductile fashion remains a topic of study, as the crystallographic nature of brittle materials is believed to have a significant impact on the critical DOC at which such materials can be machined in a ductile manner. According to theory proposed by Bifano, the critical DOC can be calculated with

$$d_c = \beta \left(\frac{E}{H_V} \right) \left(\frac{K_{IC}}{H_V} \right)^2 \qquad (1)$$

where d_c is the critical depth of cut under which ductile machining is possible, E is the Young's modulus, H_V is the Vicker's hardness, K_{IC} is the mode I fracture toughness, and β is a fitting term. However, as this equation is based on continuum mechanics and does not account for effects of anisotropy and individual dislocation mechanics that may be taking place in the machining of brittle materials, it is unclear to what extent this equation can be used. Although approximate order-of-magnitude estimates place the critical DOC around several tens to hundreds of nm, further experimentation is required to fully characterize the critical DOC.

2 MICROMILLING OF OFHC COPPER

2.1 Experimental setup

Single crystal oxygen-free high conductivity (OFHC) copper workpieces were used for this work. The single crystal copper workpieces were grown by the Bridgman technique and rated at 5N (99.999% purity), with a dimension of 12.7mm in diameter and 1mm in thickness. Three single-crystal orientation copper workpieces ((100), (110), and (111)) were tested. The workpieces were then chemically etched (etchant composition: 1 part DI water, 1 part H_2O_2, 1 part NH_4OH).

A high precision vertical machining center equipped with precision lathe, recirculating cooling for temperature stability, and high-speed spindle (36,000 RPM maximum) was used for the micromachining experiments, Figure 2 (a). Two-flute uncoated WC end mills, 150 microns in diameter, Figure 2 (b), were used in a slot-milling fashion to create a series of circular slots in each of the workpieces, Figure 3. A single radial slot in the <100> direction was milled as a reference point, and treated as an orientation of "0 degrees" for all of the experiments. A constant depth-of-cut of 10 microns was used for all experiments, and the tool path traveled in a counterclockwise motion around the center of each workpiece with a clockwise spindle operation. An alcohol-based cutting fluid was used, as it did not leave any residue and eliminated the need for post-cleaning. While a range of cutting parameters (1-3 microns feed/tooth, 9000-36000 RPM, 10 microns DOC) was used for the micromilling experiments, this was found to have little effect on the resulting burr height.

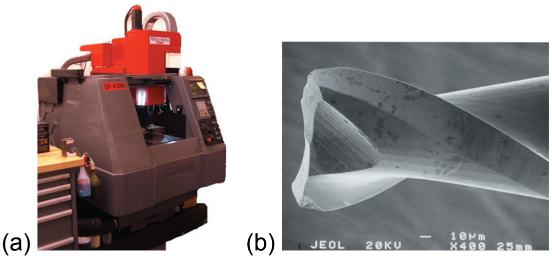

Figure 2: (a) High precision vertical machining center, (b) micro-end mill.

After the micromachining experiments were conducted, a stylus profilometer (precision: ~0.2 microns) was used to measure the burr heights. An optical microscope was also used to take pictures of the machined slots and to take pictures of the burrs.

2.2 Results

A clear difference in entrance and exit burrs at the top edges of the micromachined slots was seen, and Figure 3 shows SEM images of the micromilling burrs varying with respect to crystal orientation of the workpiece. Also, the influence of up and down milling can be clearly seen.

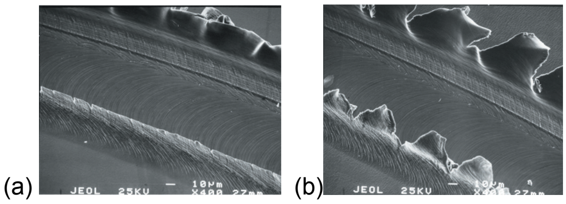

Figure 3: SEM images of burr shape variation on (100) plane at (a) 135° and (b) 180° (ft= 1µm, V_c= 17 m/min).

The burr height data was measured with the stylus profilometer, and plotted for each workpiece as a function of angle (ie. crystallographic orientation). There was very little variation in the burr height as a function of cutting speed or feed, so the average of all 12 values for each orientation was taken, and plotted vs. angular orientation on the workpiece. The burr height data for the (100) workpiece is shown in Figure 4 (a). While there is indeed some periodic variation in the burr height at the "down-milling" side (i.e. tool exit burrs) approximately every 90°, the height variation of the top burrs on the "up-milling" side (i.e. tool entrance burrs) isn't as clear. The reason for this is not clear yet.

Figure 4 (b) shows the variation in burr height for the (110) workpiece, with a clear periodic change in the burr height every 180° (as expected from the 180° symmetry in the (110) workpiece). Figure 4 (c) shows the variation in burr height for the (111) workpiece. As with the (110) workpiece, a clear periodic change in the burr height every 120° can be seen (as expected from the 120° symmetry in the (111) workpiece).

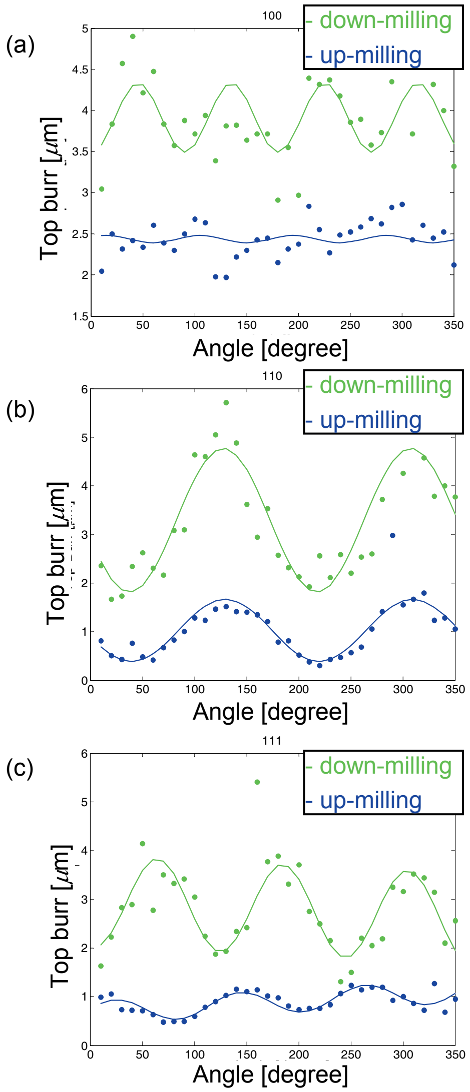

Figure 4: Burr height variation for (a) (100), (b) (110), (c) (111) workpiece.

Unlike the (100) workpiece, a strong correlation between burr height variation and crystal orientation of the workpiece material was found in the (110) and (111) workpieces. One possible explanation for this can be found from Sato's work, who explained that the amount of the side flow on the finished surface depends on the plastic anisotropy of the crystal [9]. Sato proposed that the (100) orientation has a relatively smaller anisotropy than the (110) and (111) orientations because it has a greater degree of symmetry, resulting in more equally distributed slip systems than the other orientations [9].

Of particular notice is the fact that the correlation of burr height with crystallographic orientation tends to be better on the up-milling side, rather than on the down-milling side. One possible explanation is that burrs formed at tool entrance side are typically due to Poisson-bulging of the workpiece material as the tool enters the workpiece and are not affected by the subsequent chip formation mechanism. On the tool exit side, both Poisson-bulging and the presence of residual chips change the edge condition significantly, and the correlation of burr height with chips/ragged burrs attached is not as prevalent as it is in the up-milling case. In case of burrs on the entrance side, it is unlikely that they are formed only by Poisson deformation. The chip flow on this side may also play an important role on these types of burrs on the entrance side.

3 MICROMACHINING OF MgF_2

3.1 Experimental setup

A series of ultraprecision shaping experiments were conducted on MgF_2 to examine the limit to which the material could be machined in a ductile fashion. An ultraprecision lathe at RIKEN was reconfigured in a shaping fashion to make a series of cuts of varying DOC (from 0 to 0.5 microns over 1 mm cutting length) to see to what extent MgF_2 could be machined without any excessive surface damage due to brittle machining, Figure 5. A single crystal diamond tool (0.5 mm nose radius, 0 degrees rake, 7 degrees clearance, 110 rake face) was used on the lathe, with a cutting speed of 1 mm/s. The workpiece (10 mm x 10 mm square, 1 mm thick) was initially cut in a direction along the [100] direction on the (100) plane, and the workpiece was rotated in 15 degree increments (with <100> corresponding to 0 degrees).

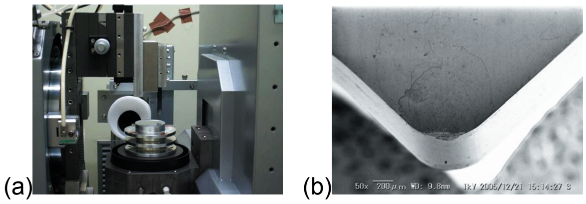

Figure 5:(a) RIKEN Ultraprecision Lathe, (b) single crystal diamond tool.

3.2 Results

Figure 6 (a) and (b) show optical micrographs of the machined region for the ductile and brittle regimes machined at the 60 degree orientation, respectively. The critical DOC was measured by locating where excessive surface cracking was initiated by brittle machining, and using an interferometric surface profilometer to measure the DOC at that location. As can be seen in Figure 6 (c) and (d), the ductile-regime machined region exhibits a very smooth surface finish of ~50 nm R_a with precise reproduction of the tool profile while the brittle-regime machined region shows excessive pitting and cracking due to the formation of surface and sub-surface cracks, with a surface finish of ~120 nm R_a.

Figure 7 shows the variation in critical DOC as a function of cutting direction. A variation in critical DOC of +/- 100 nm with an approximate periodicity of 90 degrees can be seen. As MgF_2 has a rutile configuration (tetragonal structure) with four-fold symmetry, a periodicity of 90 degrees is expected. Hence, to guarantee an optimal surface finish, the set DOC during machining needs to be maintained below a lower-bound value (about 300 nm in this case). However, for optimal process planning and production throughput, the critical DOC can be increased to as high as 500 nm at certain orientations before excessive surface cracking will take place.

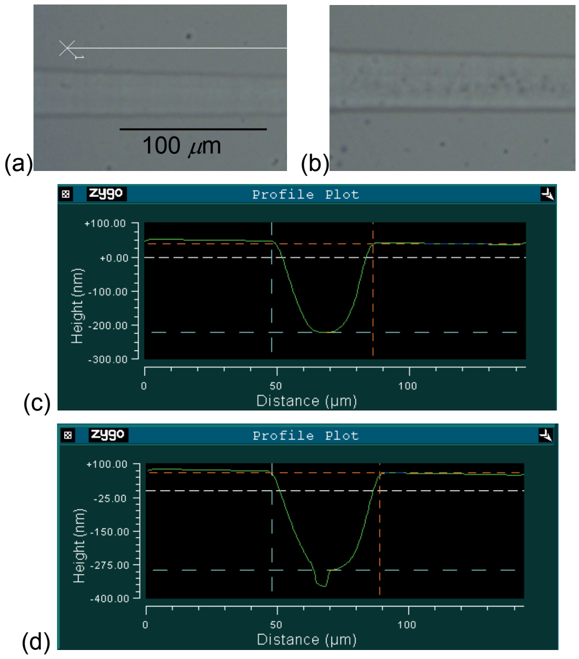

Figure 6: (a) ductile machined region, (b) brittle machined region, inteferometric surface profilometer image of (c) ductile machined region, (d) brittle machined region.

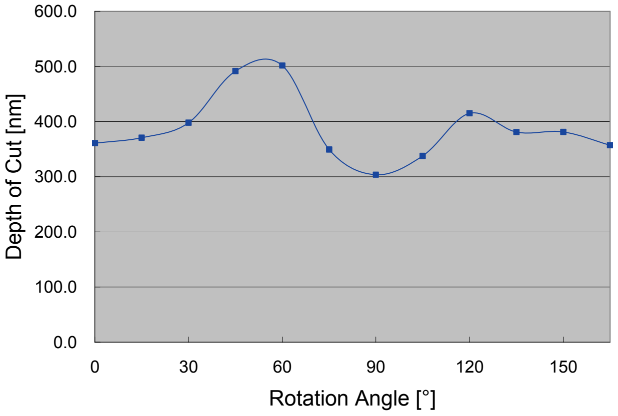

Figure 7: Variation in critical DOC with angle for ultraprecision machining of MgF_2

4 CONCLUSION

A significant variation of burr height with crystallographic orientation has been found in the micromachining of single crystal copper. Also, the critical DOC was found to vary in a manner consistent with the four-fold symmetry found in MgF_2. Some key observations were made for machining in particular crystallographic orientations:

- Micromilling process parameters did not have as significant of an effect on burr formation as crystallographic orientation.
- A distinct variation in burr height was observed as a strong function of crystallographic orientation, particularly for the (110) and (111) cases.
- The (100) machining case did not have as clear of a correlation possibly due to less anisotropy of the slip systems.
- Critical DOC can vary by +/-100 nm as a function of crystallographic orientation in ultraprecision machining of MgF_2.

The authors hope this study will bring further attention to the influence of workpiece microstructure on micromachining. Yet issues still remain and need to be investigated further in order to develop micromachining as a viable supplement to other competing manufacturing processes. Among those are:

- Further refined testing of other crystallographic orientations to see effect on surface and edge condition.
- Investigation of burr formation in other micromachining processes, such as microdrilling.
- Establishing analytical relationships between crystallographic orientation, cutting direction, and the resulting surface and edge quality**.**

5 ACKNOWLEDGMENTS

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