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Authors

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VARIATION IN MACHINABILITY OF SINGLE CRYSTAL MATERIALS IN MICROMECHANICAL MACHINING

Dae-Eun Lee[1], Manuel Deichmueller[2], Sangkee Min[1] and David A. Dornfeld[1]

[1]Laboratory for Manufacturing Automation, University of California Berkeley, CA 94720-1740, U.S.A., skmin@lma.berkeley.edu

[2]Institute of Production Engineering and Machine Tools (IFW), University of Hannover, Germany, deichmueller@ifw.uni-hannover.de

ABSTRACT

With increasing demands in manufacturing for smaller and more precise features, the advent of micromechanical machining processes, such as microdrilling and micromilling to create features at the microscale are of increasing importance. However, at the length scales found in micromechanical machining, localized variation in the microstructure (such as grain boundaries and grain orientation in polycrystalline materials) can greatly affect the machinability and final process outcome in terms of surface and edge condition; defects such as excessive roughness and burrs are of particular importance. A focused set of micromachining experiments were conducted on single crystal materials in order to further understand how surface and edge condition are affected by material crystallographic orientation. A clear correlation between burr height and crystallographic orientation was found, giving insight into optimal orientations and process parameters for acceptable micromachining process outcome.

Keywords: micromachining, single crystal material, machinability

INTRODUCTION

Current demands in the manufacturing sector, particularly with the ever-present need for miniaturization of components in everyday products such as cellular phones, consumer electronics, etc., have predicated the need for processes that can generate smaller features with a reliable and suitable degree of precision at the sub-millimeter and micron levels. 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 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.

It is important to distinguish micromachining as an entirely different process from macroscale machining that possesses several distinct characteristics which affect the final process outcome. For the purpose of this work, micromachining is defined as “machining with a tool whose dimension is in the order of the average grain size of the workpiece material and/or the specific feature being generated” or “machining with a tool whose dimension is small enough to lose isotropic homogeneity with respect to the workpiece material”, rather than machining with a tool dimension less than a specific size; a concept that has been commonly used in many publications (Schaller, 1999; Rahmann, 2001; Moriwaki, 1993, Weule, 1999).

In ultraprecision machining, the undeformed chip thickness can be on the order of a few microns or less. At these length scales, the surface and edge condition of machined features and the fundamental mechanism for chip formation are much more intimately affected by the material properties and microstructure of the workpiece material, such as ductile/brittle behavior and microtopographical features such as voids, secondary phases, and interstitial particulates (Moriwaki, 1995). When cutting single crystal materials, 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.

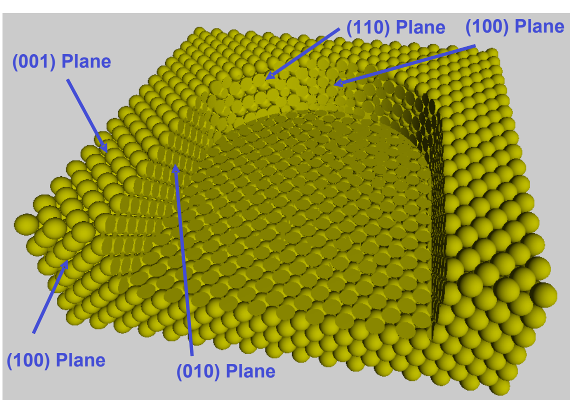


FIGURE 1. RELATIVE ORIENTATION OF CRYSTALLOGRAPHIC PLANES IN THEORETICAL MICROMACHINED TRENCH.

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 (Ueda, 1980). 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 (Sato, 1991). Similar work by Yuan et al. has demonstrated variation in surface finish and cutting force in continuous face turning of single crystal copper (Yuan, 1994), and work done by the authors has demonstrated a significant change in chip morphology and surface/edge condition in microdrilling and ultraprecision flycutting (Min, 2004). To complement the above work, this paper focuses on the observation of edge burrs as a function of crystallographic orientation in a micromilling process.

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 12.7 mm in diameter and 1 mm 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), and the resultant surfaces clearly indicate the differing crystallographic orientations for each workpiece, figures 2-4.

A Roku Roku vertical machining center equipped with precision lays, recirculating cooling for temperature stability, and high-speed spindle (36,000 RPM maximum) was used for the micromachining experiments, Figure 5a. Two flute uncoated WC endmills, 150 microns in diameter, Figure 5b, were used in a slot-milling fashion to create a series of circular slots in each of the workpieces, Figure 6. 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. The specific machining parameters for each experiment are outlined in Table 1.

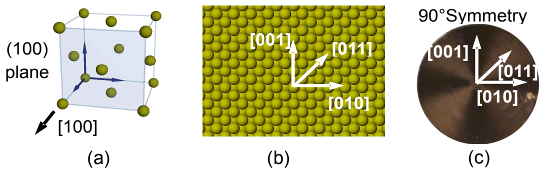


FIGURE 2. (a) (100) PLANE IN FCC CELL, (b) (100) PLANE, (c) SURFACE CHEMICALLY ETCHED (100) WORKPIECE.

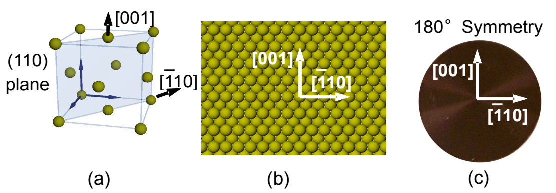


FIGURE 3. (a) (110) PLANE IN FCC CELL, (b) (110) PLANE, (c) SURFACE CHEMICALLY ETCHED (110) WORKPIECE.

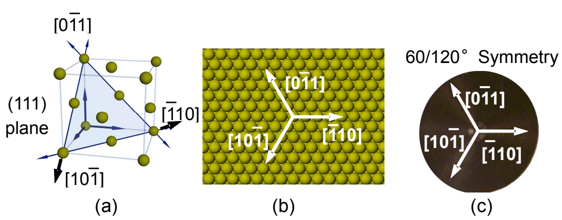


FIGURE 4. (a) (111) PLANE IN FCC CELL, (b) (111) PLANE, (c) SURFACE CHEMICALLY ETCHED (111) WORKPIECE.

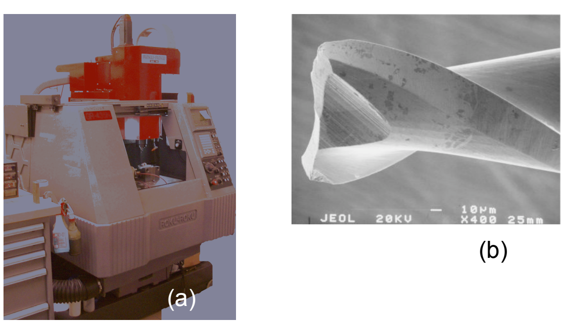


FIGURE 5. (a) ROKU-ROKU VERTICAL MACHINING CENTER, (b) ROBBJACK MICROENDMILL.

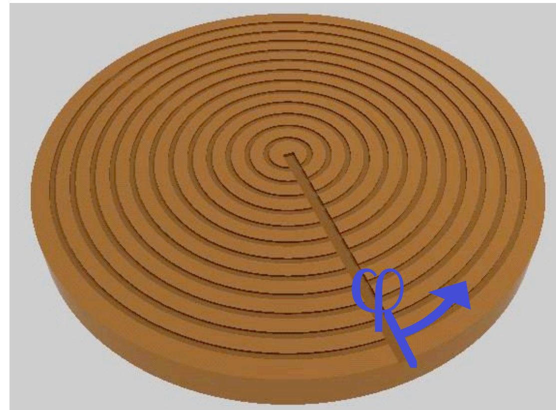


FIGURE 6. SERIES OF CIRCULAR SLOTS IN SINGLE CRYSTAL WORKPIECES (SINGLE RADIAL SLOT USED AS REFERENCE).

# of circle	Radius (mm)	Feed per tooth (mm)	Cutting speed (m/min)	Feed rate (mm/min)	Spindle speed (rpm)
1	0.48	1	4.25	18	9000
2	0.96	1	8.50	36	18000
3	1.44	1	12.75	54	27000
4	1.92	1	17.00	72	36000
5	2.40	2	4.25	36	9000
6	2.88	2	8.50	72	18000
7	3.36	2	12.75	108	27000
8	3.84	2	17.00	144	36000
9	4.32	3	4.25	54	9000
10	4.80	3	8.50	108	18000
11	5.28	3	12.70	162	27000
12	5.76	3	17.00	216	36000

TABLE 1. EXPERIMENTAL PARAMETERS FOR MICRO-SLOT MILLING.

After the micromachining experiments were conducted, a Rank Taylor Hobson Talysurf 10 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.

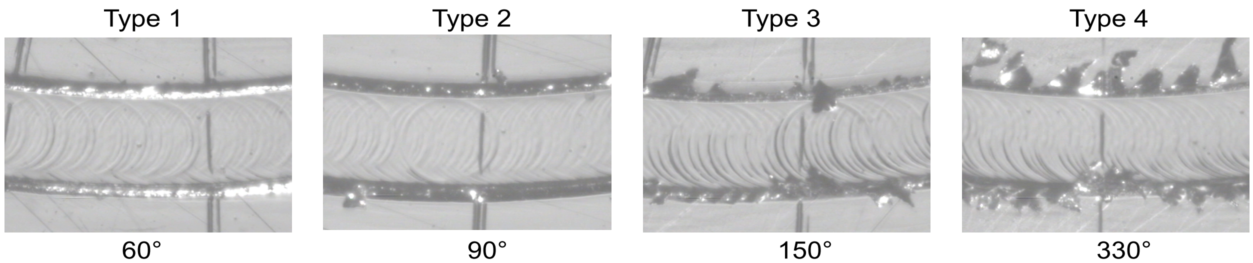


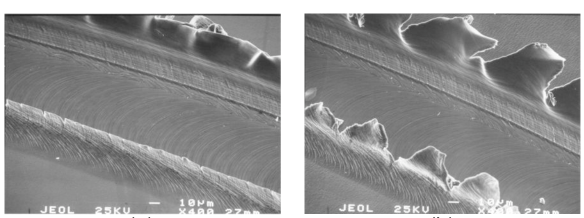
FIGURE 7. SINGLE CRYSTAL BURR CLASSIFICATIONS IN SLOT MICROMACHINING (110 WORKPIECE, ft= 1 μm, v_c= 12.75 m/min).

RESULTS

A clear difference in entrance and exit burrs at the top edges of the micromachined slots was seen, and an example of the different burr morphologies is shown in Figure 7. In general, four different types of burrs were seen.

- Type 1: uniform Poisson burr
- Type 2: mostly uniform Poisson burr with small ragged edges
- Type 3: medium ragged type burr
- Type 4: large ragged type burr

In general, the height of the burr is least for the Type 1 burr, and tends to be the largest for the Type 4 burr. However, the Type 4 burr is easier to deburr, as an ultrasonic bath treatment will remove most of the ragged burrs.



(a) (b)

FIGURE 8. SEM IMAGES OF BURR SHAPES VARIATION ON (100) PLANE AT (a) 135° AND (b) 180° (ft = 1μm, v_c = 17 m/min).

Figure 8 shows SEM images of burrs varying with respect to crystal orientation of the workpiece. Also, it clearly shows the influence of up and down milling.

The burr height data was measured with the Talysurf 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 9. While there is indeed some periodic variation in the burr height at the "down-milling" side (i.e. tool exit burrs) approximately every 90º, 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 10 shows the variation in burr height for the (110) workpiece, with a clear periodic change in the burr height every 180º (as expected from the 180º symmetry in the (110) workpiece). And Figure 11 shows the variation in burr height for the (111) workpiece. As with the (110) workpiece, a clear periodic change in the burr height every 120º can be seen (as expected from the 120º symmetry in the (111) workpiece).

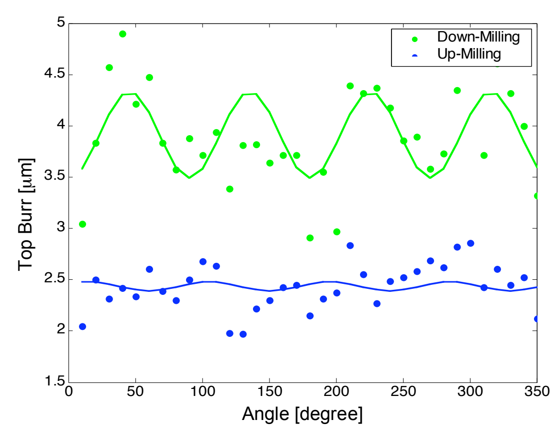


FIGURE 9. BURR HEIGHT VARIATION FOR (100) WORKPIECE.

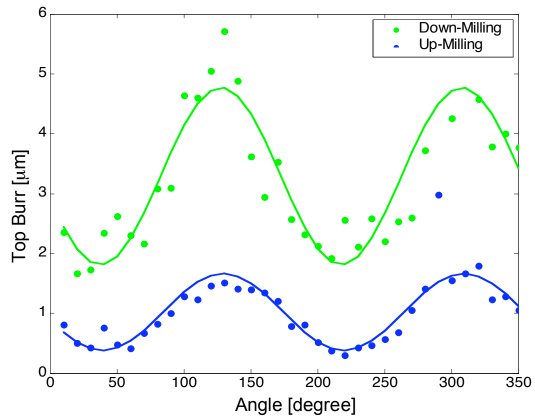


FIGURE 10. BURR HEIGHT VARIATION FOR (110) WORKPIECE.

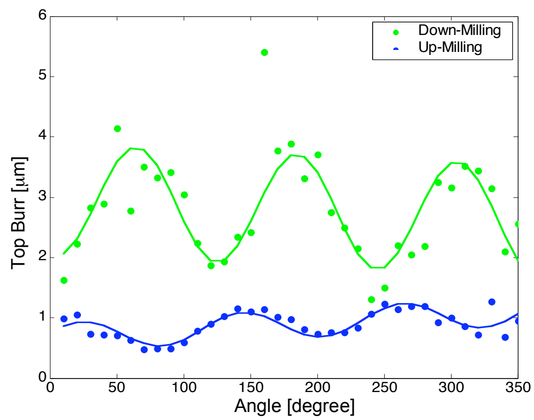


FIGURE 11. BURR HEIGHT VARIATION FOR (110) WORKPIECE.

Unlike the (100) workpiece, 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 (Sato, 1999). He and his colleagues explained the amount of the side flow on the finished surface depends on the plastic anisotropy of crystal. (100) crystal has relatively smaller anisotropy than (110) and (111) because it has many symmetries resulting in equally distributed slip systems.

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 it 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 Type 3 and Type 4 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.

CONCLUSION

A significant variation of burr height with crystallographic orientation has been found in the micromachining of single crystal copper. Certain crystallographic orientations were found to yield burrs of greater height and differing morphology. Some key observations were made for machining in particular crystallographic orientations:

- 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.
- Up-milling burrs have closer correlation to the crystallographic symmetry of the workpieces, which is believed to be due to the exclusive formation of Poisson-type burrs that are not affected by the subsequent chip formation process.
- Type 3 and Type 4 burrs on the entrance side may be influenced by the chip flow.

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.

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