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Authors

Min, Sangkee
Lee, Dae-Eun
de Grave, Arnaud
et al.

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SURFACE AND EDGE QUALITY VARIATION IN PRECISION MACHINING OF SINGLE CRYSTAL AND POLYCRYSTALLINE MATERIALS

**Sangkee Min¹, Dae-Eun Lee¹, Arnaud de Grave², Carlos M. De Oliveira Valente³,
Judy Lin¹, David A. Dornfeld¹**

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

**²Laboratoire Sols-Solides-Structures, pôle Conception
Intégrée, Domaine Universitaire, 175 rue de la Passerelle, BP 53
38041 Grenoble Cedex 9, France, degrave@hmg.inpg.fr**

**³University of Sao Paulo, Nucleus of Advanced Manufacturing,
Sao Carlos, Brazil, cmov@sc.usp.br**

ABSTRACT

The surface and edge quality of single crystal and polycrystalline copper workpieces has been observed to vary significantly as a function of crystallographic orientation. At the precision scale, the chip formation process is influenced by the microstructure of the material, such as grain boundaries and grain orientation in polycrystalline materials, and crystallographic orientation in single-crystal materials. Such variation in the microstructure has a significant effect on the resulting surface, edge, and burr topography.

INTRODUCTION

In the manufacturing of microscale structures, MEMS (Micro-Electro-Mechanical Systems) fabrication techniques based on traditional semiconductor fabrication processes such as lithography and etching have been preferred because they are proven technologies for industry application. However, inherent

characteristics of these fabrication techniques limit material selection, process reliability, and degree of design latitude. Additionally, the environmental hazards associated with these processes are a significant issue, requiring major capital investment for setup (including adequate environmental safeguards) and maintenance of production facilities.

Scaled-down versions of traditional mechanical manufacturing processes such as drilling and milling may serve as viable complementary processes to existing MEMS fabrication techniques. However, many challenges remain for the micromechanical machining process (hereafter referred to as "micromachining") to be implemented at the production level. Schaller et. al. [1] performed micromilling of microgrooves on brass and stainless steel with a width of less than 50 μm , and found aspect ratio effects of tool edge radius to the depth of cut as a noticeable difference between conventional machining and micromachining (see Figure 1).

FIGURE 1. SCHEMATIC VIEW OF THE CUTTING EDGE-WORKPIECE INTERACTION AT A GIVEN RADIUS OF CURVATURE OF THE CUTTING EDGE. (R: RADIUS OF CURVATURE OF THE CUTTING EDGE, D: DEPTH OF CUT) [1].

However, this effect can also be observed in macroscale conventional machining with negative rake angle tools. In fact, Schaller's experiments demonstrated that characteristics such as edge quality variation and the burr formation mechanism in particular were similar to those found in conventional machining. Lee et. al. [2] repeatedly demonstrated these same results. Nevertheless, in microscale fabrication and ultraprecision machining, small changes in edge and surface quality can be manifested as process-induced defects such as burrs or breakout, leading to an entire product being discarded since post-processing operations (such as deburring and edge finishing) may be too expensive or impractical to implement.

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 [1-5].

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 [6]. 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. Likewise, when cutting polycrystalline materials with these small undeformed chip thicknesses, the material removal mechanism can be highly influenced by individual grains and their respective orientation. 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 (see Figure 2).

FIGURE 2. RELATIVE SCALE COMPARISON OF CONVENTIONAL VS. PRECISION CUTTING PROCESSES [6].

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 [7]. 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 [8]. Similar work by Yuan et. al. has demonstrated variation in surface finish and cutting force in continuous face turning of single crystal copper [9]. To complement the above work, this paper focuses specifically on variation in the observed surface and edge condition of precision machined workpieces, including observation of burrs as a function of crystallographic orientation.

EXPERIMENTAL SETUP

Two types of materials, single and polycrystalline oxygen-free high conductivity (OFHC) copper were used for this work. The single crystal copper workpieces were grown by the Bridgeman 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 ($\langle 100 \rangle$, $\langle 110 \rangle$, and $\langle 111 \rangle$) were tested. The polycrystalline workpieces used were nominally 63.5 mm diameter OFHC Cu flats that were cold worked at 60% and subsequently recrystallized at 830° C for different time durations (20-60 min.), resulting in varying grain size from approximately 0.1 mm to 4 mm. The OFHC Cu flats were subsequently diced into 1 cm square pieces.

PRECISION FLYCUTTING SETUP

The machine tool used in this setup was a modified Rank Pneumo MSG-326 precision lathe equipped with a Professional Instruments Blockhead 4R air bearing spindle and precision air-bearing ways (see Figure 3). A HP laser interferometer was used to set the tool infeed position with a precision of approximately 0.1 microns. Spindle RPM was measured with a Heidenhain rotary encoder with a precision of 1 RPM.

FIGURE 3. FLYCUTTING SYSTEM SETUP.

The flycutting operation consisted of mounting a 0.274 mm nose radius single crystal diamond

tool (10° rake, 12.5° clearance) directly onto the spindle at a distance of 47.5 mm from the center. Spindle RPM was set in most cases to 420, hence generating a surface cutting speed of 2.1 m/s. A constant crossfeed of 13.3 microns/revolution was chosen for all experiments in order to maintain similar chip geometries and theoretical surface finishes across all experiments. Theoretical values of surface finish were calculated with R_{th} (peak-valley finish) of about 80 nm and R_a (centerline average surface finish) of 20 nm.

FIGURE 4. WORKPIECE/AC SENSOR ASSEMBLY SETUP.

The workpiece was held in place by a sample holder shown in Figure 4. The height of the workpiece was adjusted using shims such that the tool cut parallel to the workpiece axis. A DECI SE900-MWB acoustic emission (AE) sensor was used as a contact sensor for tool positioning. The AE sensor was positioned directly on the workpiece holder and coupled with mineral oil to minimize signal attenuation. For zeroing the tool position for each machining pass, the workpiece was slowly advanced towards the rotating tool until a slight AE signal was observed, indicating contact on the order of 1 micron in depth of cut (DOC). After using the AE sensor as a contact sensor to “zero” the tool with respect to the workpiece, a single pass with maximum nominal DOC of 20 microns (corresponding to a chord length of approximately 1 mm on the workpiece) was taken, resulting in a DOC gradient from nearly zero to a maximum of 20 microns in the middle of the machining pass. A second final pass of 20 microns was subsequently taken, in order to maintain a constant DOC across the machined surface (see Figure 5).

FIGURE 5. SCHEMATIC OF CUTTING DIRECTION AND TOOL/WORKPIECE RELATION.

MICRODRILLING SETUP

In order to investigate the influence of individual grains on burr formation in drilling, a series of drilling experiments were conducted on a Mori-Seiki TV-30 CNC tapping center with uncoated WC drills, 250 μm in diameter (see Figure 6). Polycrystalline OFHC copper workpieces with thicknesses of 130, 250, and 375 microns were used. The feed and spindle speed were varied from 0.5 mm/min to 10 mm/min and from 6000 rpm to 8000 rpm, respectively. Oil lubricant was applied manually for both lubrication and cooling.

FIGURE 6. DRILL PICTURES OF DIAMETER 250 MICRONS.

PRECISION FLYCUTTING RESULTS

For the machining of the $\langle 100 \rangle$ Cu workpiece the tool cuts in an approximate straight path parallel to the $\langle 100 \rangle$ direction with the machined surface along the $\{100\}$ plane. A Wyko NT3300 white light interferometry surface profilometer was used to measure surface finish. A smooth surface finish with an average of 23.1 nm R_a was obtained. As seen from Figure 7(a), the resulting edge shows only a slight burr extending approximately 5 microns from the edge, which is mostly uniform and doesn't exhibit any breakout. The collected chip, shown in Figure 7(b), is mostly uniform in shape.

FIGURE 7. (a) SEM SURFACE IMAGE, (b) COLLECTED CHIP, (c) WYKO SURFACE IMAGE FOR $\langle 100 \rangle$ CRYSTAL, $\{100\}$ PLANE.

The $\langle 100 \rangle$ crystal was then cut across the $\{110\}$ plane (with the same $\langle 100 \rangle$ cutting direction) by rotating the crystal in the sample holder by 45° . Figure 8 shows the SEM/Wyko surface images and collected chip. A significant change in the burr height and geometry was found for this case, with the presence of relatively large burrs still attached to the edge. The average surface finish increased to about 30.4 nm R_a . Also, a significant change in the chip topology was observed, with the edges of the chip exhibiting a feathered look, Figure 8(b).

FIGURE 8. (a) SEM SURFACE IMAGE, (b) COLLECTED CHIP, (c) WYKO SURFACE IMAGE FOR $\langle 100 \rangle$ CRYSTAL, $\{110\}$ PLANE

A simple explanation for this variation in chip topology and surface finish is offered as follows. Copper has a face-centered-cubic (FCC) structure, with a $\langle 110 \rangle / \{111\}$ slip system. Ductile plasticity and chip formation in machining is usually accomplished with the movement of dislocations along the preferred $\{111\}$ slip planes in the $\langle 110 \rangle$ directions in the shear zone ahead of the tool. Figure 9 shows the interaction of the tool with the workpiece in the orientations shown in Figures 7 and 8, with the potentially active slip systems represented by the pyramid (each face of the pyramid representing a $\{111\}$ plane with each vertex representing a $\langle 110 \rangle$ direction). It is assumed that the tool acts to force most dislocation movement in an upward fashion away from the machined workpiece, and few dislocations travel downwards back into the machined surface. In the case shown in Figure 9(a) for machining in the $\langle 100 \rangle$ direction along the $\langle 100 \rangle$ face, the dislocations on adjacent slip systems (designated as solid arrows) glide parallel to one another, hence allowing for relatively easy chip formation and a smooth surface finish. This behavior is reflected in the smooth laminar appearance of the chip in Figure 7(b). However, in the case of Figure 9(b) for machining in the $\langle 100 \rangle$ direction along the $\langle 110 \rangle$ face, dislocations gliding on the same $\{111\}$ plane collide with one another, making it

relatively more difficult (and more energy-consuming) for chip formation to take place. The interference between adjacent dislocations is manifested in both the chip topology shown in Figure 8(b) (which shows the chip as having a distorted topology with a significant amount of edge feathering), and the increase in roughness of the surface finish. Hence, for each single crystal workpiece, there exists certain crystallographic orientations which are more favorable for relatively easy dislocation glide and chip formation than other orientations. However, the exact dependency of burr formation on crystallographic orientation has yet to be established from a theoretical modeling standpoint, and remains as a topic of future research.

FIGURE 9. (a) SLIP SYSTEM/TOOL INTERACTION FOR $\langle 100 \rangle$ DIRECTION, $\{100\}$ PLANE, (b) SLIP SYSTEM/TOOL INTERACTION FOR $\langle 100 \rangle$ DIRECTION, $\{110\}$ PLANE

For machining the $\langle 110 \rangle$ workpiece shown in Figure 10, the tool cut in the $\langle 110 \rangle$ direction with the machined surface along the $\{110\}$ plane. As seen from Figure 10(a), the resulting edge has a slight burr about 10 microns in height with no breakout observed. The presence of voids and in-situ defects in this particular workpiece caused the surface finish to degrade significantly in certain parts of the machined surface, but an average surface finish of 32.6 nm R_a was measured in the regions

without defects. The collected chip exhibited a slightly ruffled appearance with some edge feathering (see Figure 10(b)). The $\langle 110 \rangle$ crystal was then cut across the $\{112\}$ plane (maintaining the same $\langle 110 \rangle$ cutting direction) by rotating the crystal in the sample holder by 54.7° . A very significant change in the edge condition was observed, with the presence of breakout and large burrs approximately 200 microns in length still attached to the surface (see Figure 11(a)). The surface finish was observed to increase slightly to $37.1 \text{ nm } R_a$, with a slight increase in the amount of feathering in the chip edge (Figure 11(c)). The $\langle 110 \rangle$ crystal was then rotated in the sample holder by 90° from its original orientation such that the machined surface was aligned along the $\{100\}$ plane. Similar-sized burrs to the previous case in Figure 11 were found (see Figure 12(a)), with the collected chip shown in Figure 12(c) exhibited a greater amount of distortion and ruffling compared to previous machining cases. A significant increase in the surface finish was found (see Figure 12(c)), with an average surface finish value of $130 \text{ nm } R_a$ being measured, indicating that this orientation is not favorable when a combination of good surface finish and smooth edge quality is desired. The key issue of note is that rotating the $\langle 110 \rangle$ workpiece to different orientations can bring about a very significant change in the burr geometry, chip topology, and surface finish.

FIGURE 10. (a) SEM SURFACE IMAGE, (b) COLLECTED CHIP, (c) WYKO SURFACE IMAGE FOR $\langle 110 \rangle$ CRYSTAL, $\{110\}$ PLANE.

FIGURE 11. (a) SEM SURFACE IMAGE, (b) COLLECTED CHIP, (c) WYKO SURFACE IMAGE FOR $\langle 110 \rangle$ CRYSTAL, $\{112\}$ PLANE.

FIGURE 12. (a) SEM SURFACE IMAGE, (b) COLLECTED CHIP, (c) WYKO SURFACE IMAGE FOR $\langle 110 \rangle$ CRYSTAL, $\{100\}$ PLANE.

Figures 13 and 14 show SEM pictures of the edge for a $\langle 111 \rangle$ workpiece. Figure 13 shows the edge and surface of the workpiece machined along the $\{110\}$ plane in the $\langle 111 \rangle$ direction, with a resulting surface finish of $25.6 \text{ nm } R_a$. An extremely smooth and homogenous chip was obtained for this machining case (see Figure

13(c)). After machining in this configuration, the workpiece was rotated by 30°, and Figures 14(a) and 14(c) shows the edge and surface of the workpiece being machined along the {112} plane, respectively. An average surface finish of about 26.2 nm R_a was measured, with the collected chip exhibiting an increased amount of distortion and ruffling (see Figure 14(b)). While the first cutting case in Figure 13 shows only a slight burr (about 5 microns in height) extending from the edge with several large burrs attached, the second case in Figure 14 shows a continuous burr with an increased amount of edge distortion.

FIGURE 13. (a) SEM SURFACE IMAGE, (b) COLLECTED CHIP, (c) WYKO SURFACE IMAGE FOR <111> CRYSTAL, {110} PLANE.

As a further test, the <110> workpiece was rotated to several specific orientations as shown in Figure 15 at different cutting speeds. The first column of Figure 15 shows an initial series of cuts that were made at a cutting speed of 2.1 m/s on the <110> workpiece at four orientations where the machined surface was parallel to the {110}, {111}, {112}, and {100} planes, respectively. The cutting speed was increased to 6.8 m/s (1330 RPM), and the resulting surfaces are shown in the second column of Figure 15. A significant variation in the edge condition was found with significantly less burrs found at the {110}, {111}, and {112} orientations at higher cutting speeds. Higher speeds also led to a slight decrease in overall burr height.

FIGURE 14. (a) SEM SURFACE IMAGE, (b) COLLECTED CHIP, (c) WYKO SURFACE IMAGE FOR <111> CRYSTAL, {112} PLANE.

FIGURE 15. SEM IMAGES FOR <110> CRYSTAL (a) {110} PLANE (b) {111} PLANE (c) {112} PLANE (d) {100} PLANE

Figure 16 shows two polycrystalline copper workpieces (average grain diameter 250 microns) machined with the same experimental parameters as for the single crystal experiments. After machining, the resulting surfaces were chemically etched to reveal the underlying grain structure. In both cases, the resulting edge topology and burrs varied significantly as a function of grain orientation, with each grain exhibiting a different burr height.

FIGURE 16. SEM IMAGES OF VARYING BURR HEIGHT IN POLYCRYSTALLINE COPPER WORKPIECES.

MICRODRILLING RESULTS

Drilling burrs depend on many process parameters, with feed rate as a dominant factor [10-13]. In general, a crown burr forms at higher feed rates, and a uniform burr forms at lower feed rates in most ductile metals (see Figure 17). The boundary between these two distinctive burr types mostly depends on material properties.

FIGURE 17. TYPICAL DRILLING BURRS IN DUCTILE METALS [13].

The maximum feed rate used during the microdrilling experiments was 10 mm/min. During the experiments, no crown burrs were observed. Typical burr types found were the uniform burr and uniform burr with a drill cap, as shown in Figure 18. The shapes of the burrs were not entirely unlike those found in conventional macroscale drilling, indicating that the burr formation mechanism is similar to that in conventional drilling. During the burr initiation stage, as the drill advances, the plastic zone at the center of the drill tip reaches the exit surface of the workpiece. The thin layer of the plastic zone in the uniform burr does not have enough support to be cut by the drill, so during the development stage, very little cutting near the center of the drill occurs, yet cutting is still dominant near the edge of the drill. The plastic zone that initially formed near the center of the drill area then expands to the edge of the drill (see Figure 19(a)). With expansion of the plastic zone and edge cutting, initial fracture occurs at the edge of the drill and creates a uniform burr (see Figure 19(b)). Due to imperfections in the process, initial fracture does not occur at some of the edges and it leads to the formation of a drill cap as shown in Figure 19(d).

FIGURE 18. BURR TYPES FOUND IN MICRO-DRILLING (a) UNIFORM BURR (10 mm/min, 8000 rpm) (b) UNIFORM BURR WITH A DRILL CAP (5 mm/min, 8000 rpm).

FIGURE 19. BURR FORMATION PROCESSES
(a) PLASTIC ZONE EXPANDING FROM CENTER TO EDGE (b) INITIAL FRACTURE AT THE EDGE (c) FRACTURE SPREADING ALONG THE EDGE (d) FINAL BURR WITH DRILL CAP.

Overall aspects of microscale burr formation are similar to macroscale burr formation, yet it was observed that burr height and topology varies as a function of grain orientation. Since the tool diameter used was on the order of grain size, in most cases, the cutting physics taking place at the tool edge varies as the tool moves from one grain to another. However, since the cutting direction of drill changes continuously during the process, and individual grain orientations are not known in advance, it is very difficult to establish a clear relationship between these two factors for drilling. However, Figure 20 clearly shows that one grain orientation favors a particular cutting direction, which leads to a ductile-like cutting mode and in turn a larger burr.

(a) Burr within grain boundary (10 mm/min, 7000 rpm)

(b) Burr across grain boundary (5 mm/min, 6000 rpm)

(c) Burr over small grain (5 mm/min, 7000 rpm)

(d) Grain boundary follows burr topology (10 mm/min, 8000 rpm)

FIGURE 20. MICRODRILLING BURR FORMATION ACROSS DIFFERENT GRAINS.

CONCLUSIONS

A significant variation between surface/edge condition and crystallographic orientation has been found in the precision machining of single and polycrystalline copper. Certain crystallographic orientations were found to yield rougher surface finish, as well as significant burrs and breakout at the tool exit edge. Some key observations were made for machining in particular crystallographic orientations:

- Machining of the $\langle 100 \rangle$ and $\langle 111 \rangle$ workpieces tended to yield the smoothest surface finish ranging from 20-30 nm R_a , whereas the $\langle 110 \rangle$ crystal orientation with a $\{110\}$ machined plane exhibited the roughest surface finish of 130 nm R_a .
- The $\langle 100 \rangle$ and $\langle 110 \rangle$ workpieces exhibited the greatest amount of variation of burrs and breakout at the exit edge and chip topology as a function of the angular orientation of the workpiece, corresponding to a variation in interaction between the tool and activated slip systems.

It was also found that grain orientation affected burr formation in drilling of polycrystalline copper. A single material may produce a ductile-like cutting mode in one grain and brittle-like cutting in another, indicating that favorable and non-favorable cutting orientations for good surface and edge condition exist as a function of crystallographic orientation. These observations demonstrate the importance of further research in this field.

The authors hope this study will bring further attention to the influence of workpiece microstructure on micromachining. Many issues still remain and need to be investigated further in order to develop micromachining as a viable supplement to existing MEMS fabrication 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 micromilling.

- Establishing analytical relationships between crystallographic orientation, cutting direction, and the resulting surface and edge quality.

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