Experimental Study on the Surface Integrity and Chip Formation in the Micro Cutting Process

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Abstract
The micro cutting mechanism is very different from the macro cutting process, where the workpiece is not considered as isotropic solid. Hence the effect of microstructure on the micro cutting mechanism needs to be further studied. In this paper, pure copper with two different grain sizes was machined by the natural single crystal diamond cutting tool, in order to study the effect of microstructure on the machined surface integrity and chip formation, during the micro cutting process. According to the experimental results, the hardness of original pure copper was higher than the annealed pure copper due to the grain boundary strengthening. The grain boundary can be found in the machined surface of annealed pure copper. As for original pure copper, the grain boundary is absent and the surface had only traces of tool path. In the grain boundary, the height of peak-valley is larger than that inside grain. The following indicates that the reduction of grain size will reduce the effect of microstructure on the surface integrity in the micro cutting process. With the decreasing of feed rate, cutting chip’s shape changed from continuous to segmented at the same depth of cut (DOC) in both original and annealed pure copper. The chip of annealed pure copper is more segmented than the original copper at some cutting conditions.

Keywords: Micro cutting, surface integrity, chip formation, grain boundary, pure copper

1 Introduction

Metal cutting is a widely used in manufacturing process to produce components with its high efficiency and accuracy considering industry standards, as in automotive, aerospace, biotechnology, electronics and communications. (Chae, Park, & Freiheit, 2006). With the high requirement of surface
integrity and miniaturization of components, the micro cutting technologies are developed in recent years to achieve mirror-like surface and micro component, such as diamond cutting technology, micro milling and micro turning technology (Ding & Rahman, 2012; Lu & Yoneyama, 1999; Lee, Cho, & Ehmann, 2008). Those technologies have been widely used in the industries to manufacture optical device, mold and MEMS systems.

In the micro cutting process, DOC is very small, which results in the mechanism of cutting very different from the conventional cutting process. A phenomenon called size effect which is characterized by a nonlinear increase in the specific cutting energy, i.e. energy per unit volume with decrease in uncut chip thickness, is very common in the micro cutting process (Lai, Li, Li, Lin, & Ni, 2008). In the conventional cutting process, which is also referred as macro cutting process, the workpiece is usually treated as isotropic solid. The cutting force, temperature, surface roughness caused by side flow and cutting tool wear are mostly affected by the macro flow stress of material, which can be tested by the Split Hopkinson Pressure Bar (Sutter, Molinari, List, & Bi, 2012; Chen, Li, He, & Ren, 2014; Paturi, Narala, & Pundir, 2014). The workpiece material used in most practical engineering application is usually composed of many grains of varying grain size, crystallographic orientation and grain boundary, which is also known as polycrystalline. The mechanical properties of polycrystalline material highly depend on the microstructure (Yuan, et al., 2014; Germain, Kratsch, Salib, & Gey, 2014; Gonzalez, Simonovski, Withers, & Fonseca, 2014). In the micro cutting process, the cutting edge moves forward in a single grain near the surface of the workpiece. The crystallographic orientation, grain boundary and other defects in the gain will have a strong effect on the cutting mechanism. Therefore, the workpiece machined cannot be regarded as isotropic solid anymore. To improve the manufacturing accuracy, the effect of microstructure on the cutting mechanism in the micro cutting process needs to be addressed.

Surface integrity which includes mechanical properties, metallurgical states and topological parameters has a great effect on the quality and performance of a product, such as fatigue, reflectance and wear (Ulutan & Ozel, 2011). Although many research work addressed the effect of material microstructure on the cutting force by analytical, Finite Element Analysis (FEA) or Molecular dynamics (MD) simulation method (Tajalli, Movahhedy, & Akbari, 2014; Komanduri, Chandrasekaran, & Raffa, 1999), there is not much know about the effect of material microstructure on the surface integrity in the micro cutting process.

In this paper, two different grain sizes pure coppers were obtained by the heat treatment method. Then the micro cutting tests of two different grain sizes pure copper with natural single crystal diamond cutting tool were carried out in an ultra-precision machine tool. The microstructure of material was examined by the optical microscope. The chip was investigated in the scanning electron microscope (SEM). Furthermore, the white light interferometer was used to obtain the 3D profile of the machined surface. The relationship between the microstructure and chip formation, surface integrity was also analyzed.

2 Experiment

2.1 Workpiece material

The workpiece material used in this experiment is the commercially pure oxygen-free high conductivity (OFHC) copper, which has less than 0.05% residual deoxidation elements and oxygen and is widely used in the optical device (Lin & Lo, 1997). In order to study the effect of material microstructure on the chip formation and machined surface integrity of the micro cutting process, the material investigated had two different grain sizes. The first one was in its factory state. The other workpiece was in its annealed state, which was achieved by keeping the factory state pure copper in a vacuum furnace in 600°C for 4 hours and then was cooled to room temperature in the furnace.
To examine the metallographic microstructure, the sample was firstly ground in 600-, 1200-, and 2000-grid waterproof silicon carbide paper and polished in wool felt, then it was etched in FeCl₃ for a few seconds. The microstructure was examined in an optical microscope, as shown in Figure 1.

Material hardness was tested by the Vickers hardness tester (Wilson Hardness TUKON™ 2500). The cylindrical sample was used in the test. Dimension of the sample was 20mm in height and 18.5mm in diameter. Nine points along the radial direction in the end surface of the sample were measured. The load was 0.1 kilogram and the loading time was 10 seconds.

![Figure 1: Microstructure of (a) original pure copper and (b) annealed pure copper](image)

2.2 Machining arrangement

The cutting experiment was carried out in an ultra-precision machine tool, having very high stiffness and accuracy, as shown in Figure 3 (a). It can be seen from Figure 3 (a) that the specimen was clamped and rotated in the spindle of the machine tool and the cutting tool was fed towards the radial direction of the specimen end surface. The cutting tool used in the cutting experiment was a natural single crystal diamond (NSD) cutting tool which can achieve a much sharper cutting edge than Polycrystalline diamond (PCD), Cubic Boron Nitride (CBN), Tungsten Carbide (WC) cutting tool (Zhang, Kumar, Rahman, Nath, & Liu, 2011). As shown in Figure 3 (b), the nose radius of cutting tool was 2.0mm. The rake angle was 0° while the relief angle was 5°. The radius of cutting edge was about 300nm as stated by the producer.

![Figure 3: Machining system (a) ultra-precision machine tool (b) natural single crystal diamond cutting tool](image)
The cutting parameters are illustrated in Table 1 and Table 2. The end surface of the specimen was pre-machined 3 times at 1200rpm (rotation speed), 8μm (DOC), 8mm/min (feed) with coolant. Then the specimen was machined 2 times by the designed parameter. For the first time, the chip was collected without coolant. As for the second time, the machined surface was obtained with coolant. The coolant used in the cutting process was alcohol mixed with kerosene (MQL).

Table 1: Cutting parameters of original pure copper

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<thead>
<tr>
<th>Number</th>
<th>Rotation Speed /rpm</th>
<th>DOC /μm</th>
<th>Feed /mm/min</th>
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<tr>
<td>1</td>
<td>1200</td>
<td>4</td>
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<td>3</td>
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Table 2: Cutting parameters of annealed pure copper

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<th>Number</th>
<th>Rotation Speed /rpm</th>
<th>DOC /μm</th>
<th>Feed /mm/min</th>
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At the end, the chip collected and machined surface were investigated in the scanning electron microscope (SEM) and white light interferometer to further study relationship between the microstructure and chip formation, surface integrity.

3 Results and discussion

3.1 Workpiece material property

It can be seen from Figure 1 that the grain size of annealed pure copper was higher than the original pure copper because of grain growth under high temperature. The grain size of annealed pure copper ranged from 100μm to 200μm while the grain size of original pure copper was equal to ten microns. Some annealed twins can be found in the annealed pure copper grains due to the plasticity deformation and recrystallization property of FCC crystal (Benchabane, Boumerzoug, Gloriant, & Thibon, 2011). And most of the annealed twins traversed through the grain completely.

The mechanical property of material is also affected by the material microstructure. As shown in Figure 4, the average hardness of original pure copper (107 HV) was higher than the annealed pure copper (57 HV). When the material is under plastic deformation, the dislocation will move through the material. The grain boundary in the material can be viewed as a barrier, most of the dislocation will stack in the grain boundary and results in the increase of strength. The smaller the grain size, the more grain boundaries will be in the material, and strength of material will be higher. This phenomenon is also referred as Hall-Petch effect (Lefebvre, Devincre, & Hoc, 2005).

Figure 4: Hardness comparison between original and annealed pure copper
3.2 Machined surface integrity

The comparison of machined surface between two different grain sizes pure coppers at the same cutting parameters (rotation speed=1200rpm, DOC=4μm, feed=8mm/min) is shown in Figure 5.

![Figure 5: Comparison of machined surface between (a) original pure copper and (b) annealed pure copper](image)

As Figure 5 shows that the mirror-like surface was achieved in current cutting conditions, which meant that both machined surfaces had a very low surface roughness after cutting. The machined surface topography was investigated in white light interferometer, as show in Figure 6. The 3D surface roughness (Sa) of original pure copper was 7.8nm while annealed pure copper was 12.0nm. According to Figure 6, there was only tool path remaining in the original pure copper while both the tool path and the grain boundary can be found in the machined surface of annealed pure copper. As shown in previous research works, the material will flow towards the sides near the cutting edge during the cutting process, which is obviously in the soft material (Zong, Huang, Zhang, & Sun, 2014). Plastic flow of material will significantly increase the surface roughness. As analyzed before, the hardness of original pure copper was higher than annealed pure copper. Therefore, plastic flow in the annealed pure copper was more dominant than the original pure copper. The microstructure in the annealed pure copper is the other factor that increases the surface roughness. The 3D surface topography of annealed pure copper is shown in Figure 7.

![Figure 6: Machined surface of (a) original pure copper and (b) annealed pure copper in white light interferometer](image)
As shown in Figure 7, the height of peak-valley was larger than that inside of grain. The mechanical property of the grain boundary is very different from grain. Some studies have pointed that the grain boundary has higher strength than grain (Kalidindi & Vachhani, 2014). In the cutting process, the material piled up near the grain boundary as the cutting tool traveled across the grain, which resulted an increase in surface roughness. To decrease the surface roughness, reduction of microstructure and improvement of material hardness is suggested.

### 3.3 Chip formation

The cutting chips of two different grain sizes pure coppers collected from the micro cutting experiments without coolant were investigated in the SEM, as shown in Figure 8 and Figure 9.

From Figure 8 and Figure 9, it can be seen that with the decrease of the feed, the chip’s shape changed from continuous to segmented at the same DOC in both original and annealed pure copper. The chip generated while machining annealed pure copper was more segmented than the original copper when the feed=2mm/min. As Figure 10 shows, the free surface and the back surface of the chip were very different from each other. The free surface was very rough and the lamella pattern can be found on the free surface while the back surface was very smooth. The lamella pattern is caused by dislocation gliding from the inside to the free surface along the glide plane. As mentioned before, the pure polycrystalline copper is a composition of different crystallographic orientations and glide planes thus causes the non-uniformity in lamella pattern. As Figure 8 and Figure 9 show, the chip had two edges, one edge (edge A) showed many cracks while the other edge (edge B) showed fewer crack. The edge A was the thinnest part in the chip while edge B was the thickest part. Decreasing the feed resulted thinner chips, which became weaker. The crack generating in the edge A caused by the high stress near the tool had more possibility of spreading to edge B as the average thickness of the chip.
became small. Thus, chip’s shape changed from continuous to segmented when the feed decreased (Tauhiduzzaman & Veldhuis, 2014).

4 Conclusions

In this study, pure copper with two different grain sizes was machined by the natural single crystal diamond cutting. Hardness of original pure copper was 107 HV while hardness of annealed pure copper was 57 HV. The cutting chip and machined surface were characterized by a microscope. According to experimental results, it can conclude that:

1) The mechanical property and microstructure had a significant effect on the surface roughness of the machined surface. The grain boundary can be found in the machined surface of annealed pure copper, which increased the surface roughness. In order to decrease the surface roughness, reduction of microstructure and improvement of material hardness suitable are suggested.

2) The lamella pattern caused by the gliding of dislocation along the glide plane was found on the free surface of cutting chip, which made it rougher than the back surface of cutting chip.

3) As the feed decreased, the cutting chip’s shape changed from continuous to segmented at the same DOC in both original and annealed pure copper. The annealed pure copper was more segmented than the original copper when the feed=2mm/min.

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References


