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S. ISLAM, R. IBRAHIM AND N. KHANDOKER

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The mechanics of single crystal Cu machining at nanoscale

S. Islam^a, R. Ibrahim^a and N. Khandoker^a

^a Department of Mechanical and Aerospace Engineering, Monash University, Clayton, Victoria 3800, Australia

Abstract

The objective of this study is to identify the mechanics of machining at nano scale on single crystal Cu with (100), (110) and (111) crystallographic orientations. A nano indenter equipped with a nano scratching attachment was used for machining operations and in situ observation of a nano scale groove. As a machining parameter, the depth of cut was varied in this study. Both elastic and plastic deformations were significant during machining. The plastic deformation was responsible for causing the ploughing and cutting mechanisms to produce the nano scale groove. The presence of the ploughing and cutting g mechanisms was determined based on the pile up volume and the cutting volume respectively.

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Keywords: Ploughing mechanism, Abrasive wear, cutting mechanism, nanomachining.

1. Introduction

The nano scale machining is performed within a grain because the machining length and depth of cut are usually less than the grain size of a polycrystalline aggregate [1, 2]. In conventional analysis the polycrystalline material were considered as an isotropic and homogenous. The crystallographic orientation of the material being cut exerts a great influence on the cutting behaviour and machined surface.

The material behaviour was assumed to be rigid plastic in nature during traditional machining operation [3]. Therefore, by considering the indentation depth to be constant, the actual elastoplastic deformation mechanism was ignored by avoiding the relaxation phenomenon of the material. In this study, this relaxation phenomenon is introduced in terms of percentage of elastic recovery. Furthermore, the elastoplastic deformation is utilized to identify the abrasive wear mechanism during machining operations [4]. This wear mode in micro scale was expressed as the sum of three processes: cutting, cracking and ploughing [5-9]. However, some research have been conducted to distinguish nano scale abrasive wear mechanisms using polycrystalline material [10, 11]; there is a lack of experimental data to understand the physics of nano scale abrasive wear mechanism on different crystallographic orientation of the material.

The aim of this study is to investigate the deformation behavior and the abrasive wear mechanism of micron sized Cu samples with three crystallographic orientations such as Cu (100), Cu (110) and Cu (111) which were considered to analyze in nano machining. The effect of the depth of cut on elastoplastic

deformation behaviour was studied. The plastic deformation of the material was indicated by the pile up which was utilized to distinguish between the ploughing and cutting modes of abrasive wear mechanism.

2. Experimental Details

Nanomachining was conducted on the (100), (110) and (111) orientated single crystal copper surfaces. These three single crystal Cu surfaces with different orientations were prepared for the nano machining tests with a dimension of 10 mm diameter and 1 mm thickness. These Cu samples used herein were produced by the MaTeck Company in Germany. The orientation accuracy of the Cu single crystal is $<.01^\circ$. The average surface roughness was measured by Hysitron Tribolab (2008).

In these experiments, nano machining was performed on a Hysitron Tribolab (2008) nanomechanical testing instrument with the scratching method, using the displacement control mode. The diamond conical tool having a tip radius of 100 nm and 60° cone angle was used for the machining purpose and in situ observation was performed. All experiments were performed under room temperature and normal atmospheric conditions with the temperature range of 20-24°C and relative humidity range of 45-50%. The topographic scanning method was employed to analyse the depth of the machined surface. The area of the topographic measurement was $10x10 \ \mu\text{m}^2$. During scanning, 20 $\mu\text{m/s}$ tip velocity and 1 Hz scan rate were used. As a machining parameter, the depth of cut and the machining velocity were varied to investigate the abrasive wear mechanism with the elastoplastic deformation behaviour during nanomachining.

3. Results & Discussion

3.1. Determination of elastic recovery

In situ, the scanning operation was performed by the nano indenter to identify the post machining groove profile as shown in Fig 1. The groove depths were measured and Fig 2 shows the variation in the obtained groove depth with change in the depth of cut. It present that the obtained groove depth increased with the increase of the depth of cut. It also found that the obtained groove depths were larger when machining was performed on Cu (110) plane than that on Cu (100) and Cu (111) planes at different depth of cuts. These obtained depth values were utilized to calculate the percentage of elastic recovery using the following expression:



Fig 1 Schematic diagram of the machined profile.



Fig 2 Variation in the obtained groove depth with change in the depth of cut on single crystal copper of (100), (110) and (111) planes.

Fig 3 shows the variation in the elastic recovery (%) with change in the depth of cuts. The value of the elastic recovery of Cu at different crystallographic planes was inverse to the obtained groove depth. For different crystallographic orientations of the materials, the percentage of elastic recovery decreased with increase in the depth of cut due to increase of the generated forces. The elastic recovery was lower in the case of Cu (110) plane compared to the other crystallographic orientations. This result shows that Cu experienced on average (40-50) % elastic recovery over the range of depth of cuts for three crystallographic orientations. These percentage values reveal that the primary deformation behaviour were relatively more elastic in nature after nanomachining operations on different crystallographic orientations to the percentage of elastic recovery for Cu material indicates that the elastic part becomes significant relative to the plastic, whereas for the traditional machining operation, elastic deformation is considered as a negligible part.



Fig 3 Variation in the elastic recovery with change in the depth of cut on single crystal copper of (100), (110) and 111 planes.

3.2. Determination of abrasive wear mechanism

Pile up volume was formed due to the plastic deformation of the material. When machining was performed on single crystal planes, only the conical tip was used as a cutting tool because of it's symmetrical shape. Fig 4 shows that the pile up formed on both sides of the scratch length using the conical tool for Cu (100), Cu (110) and Cu (111) planes. However, the volume of pile up generated on left side of the scratch is a little bigger than that of right side. This is because an eccentricity exists in the tip mount system. This plastically deformed pile up volume (due to the generation of hydrostatic pressure by the cutting tool) was utilized to characterize the abrasive wear mechanism in the nano machining operations. Fig 5 and Fig 6 present the pile up volume (V_p) and the groove volume (V_g) respectively for the undertaken nano machining conditions with the variation of the depth of cut for different crystallographic orientations.



Fig 4 3D view of the machined surface morphology (up) and YZ plane (bottom) of the Cu single crystal after nanomachining at the 150 nm depth of cuts. (a)Cu (100), (b) Cu (110) and (C) Cu (111) planes.



Fig 5 Variations in the pile up volume with change in depth of cut on single crystal copper of (100), (110) and (111) planes.

Both figures (5 and 6) reveal that there was not significant difference for the pile up volume and groove volume in different crystallographic orientations at the same depth of cut. The calculated pile up and groove volumes were utilized to determine the cutting volume. Since it was difficult to find out and collect the nano scale chip from the machined surface, therefore these cutting volume were utilized to identify the cutting mechanism.



Fig 6 Variation in the groove volume with change in depth of cut on single crystal copper of (100),(110) and (111) planes.

The cutting volume V_c , was defined as the difference between the groove volume, V_g , and the pile-up volume, V_p , from topographic measurements (along the sliding direction x) as shown in Fig 1. If the resulting cutting volume, V_c , after the machining operations of the surface is positive then it indicates that the cutting mechanism is present with the ploughing mechanism during the nano machining operation. Otherwise, the ploughing mechanism is the only mode of abrasive wear mechanism to obtain the groove volume.



Fig 7 Variation in the cutting volume with change in depth of cut on single crystal copper of (100), (110) and (111) planes.

Fig 7 shows the variation in the cutting volume with change in the depth of cut. The value of the cutting volume was found to be zero up to 100 nm depth of cut which is equal to the radius of the cutting

tool. This signifies that up to 100 nm depth of cut, the cutting mechanism was not present in this type of machining conditions. Thus the ploughing mechanism due to plastic deformation was the only factor for generating the groove volume. Beyond 100 nm depth of cut, the cutting volume was increased with the increase of the depth of cut for different crystallographic orientations. Therefore, cutting was an additional mechanism that contributed to the groove formation along with the ploughing mechanism after 100 nm depth of cut. When the depth of cut was equal or less than the cutting tool tip radius the effective rake angle was more negative, therefore the adhesion between the material and the rake face of the tool became sufficiently great to prevent chip formation and the material was displaced by the ploughing mechanism. The results revealed that there was not enough variation of the pile up and groove volumes in different crystallographic orientations; however, the cutting volume was larger when machining was performed on Cu (111) plane than Cu (100) planes.

4. Conclusion

The following conclusions can be drawn from the presented experimental results.

- The elastic recovery (%) decreases with an increase in the depth of cut. After a single scratching operation, the deformation mechanisms are highly elastic in nature due to ~ (40-50) % elastic recovery for different crystallographic orientations of Cu planes. Cu (111) plane experienced 5% and 10% higher elastic recovery than Cu (100) and Cu (110) planes respectively.
- For machining different crystallographic orientation of Cu plane, there is not significant difference of the generated pile up and groove volume at different crystallographic planes due to the variation of the depth of cuts. However, largest cutting volume is observed when machining is performed on Cu (111) plane. Therefore, the machinability of the Cu (111) plane is better than Cu (110) and Cu (100) planes.

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