Effect of Machining Velocity in Nanoscale Machining Operations

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Sumaiya Islam[*1], **Raafat Ibrahim**[2], **Noman Khondoker**[1]

[1]Department of Mechanical Engineering, Faculty of Engineering & Science, Curtin University Sarawak, CDT 250 Miri, Sarawak 98009, Malaysia.

[2] Department of Mechanical and Aerospace Engineering, Monash University, Clayton, Victoria 3800, Australia.

*E-mail: sumaiya.islam@curtin.edu.my

Abstract. The aim of this study is to investigate the generated forces and deformations of single crystal Cu with (100), (110) and (111) crystallographic orientations at nanoscale machining operation. A nanoindenter equipped with nanoscratching attachment was used for machining operations and in-situ observation of a nano scale groove. As a machining parameter, the machining velocity was varied to measure the normal and cutting forces. At a fixed machining velocity, different levels of normal and cutting forces were generated due to different crystallographic orientations of the specimens. Moreover, after machining operation percentage of elastic recovery was measured and it was found that both the elastic and plastic deformations were responsible for producing a nano scale groove within the range of machining velocities from 250-1000 nm/s.

Keywords-Nano machining; Single crystal; Elastic recovery; Pile up

1. Introduction

From the view point of learning from nature, the controlling of crystal orientation is accounted to be a major subject for material processing. In nano machining, the machining length and depth of cut are usually less than the grain size of a polycrystalline aggregate [1] and machining is performed along the direction of the grain. The polycrystalline work piece material may be considered to be an isotropic and homogenous continuum in the conventional analysis and must be treated as a series of single crystal with random orientations and anisotropic properties. Therefore, the crystallographic orientation of the material being cut exerts a great influence on the cutting behaviour and machined surface. Most

studies of the cutting mechanism are performed under the assumption that the material is isotropic and is a homogenous continuum [2] and that the effect of material anisotropy is often not included in the theoretical analysis.

Atomic Force Microscope (AFM) is a well recognised tool employed for nano machining operations for measuring mechanical characteristics [3-4].The convention of the AFM based lithographic technique is that the machined surface scale of the structure is solely determined by the geometry of the AFM probe [5-6]. The nanoindenter produced by Hysitron utilises the same mechanism to create a scratch. However, a diamond probe is placed with the tool holder instead of the cantilever attachment used in AFM. The advantage of using a nano indenter is to avoid the effect of the cantilever's geometry, stiffness and their respective calibration reliability on the measured nano machining parameters.

Using the indentation method, the deformation behaviour of various materials have been extensively reported by varying the tip geometry and tip orientation [7], and in most cases the material behaviour was assumed to be rigid plastic in nature [8]. However, some research have been conducted to analyse the deformation behaviour with the variation of the depth of cut [9-12] considering different crystallographic orientation, however, variation of the machining velocity was not considered. Therefore, in this paper, the effect of the machining velocity on the generated forces as well as the deformation behaviour of Cu samples with different crystallographic orientations were analysed with nano indenter.

2. Experimental details

Nano machining 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°.

In these experiments, nano machining was performed on a Hysitron Tribolab (2008) nano mechanical testing instrument with the scratching method, using the displacement control mode. As a machining parameter, the machining velocities were varied from 250nm/s to 1000 nm/s, to investigate the generated forces (normal and cutting forces) and elastoplastic deformation behavior during nano machining.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 μm^2. During scanning, 20 $\mu m/s$ tip velocity and 1 Hz scan rate were used.

3. Results and discussion

To evaluate the effect of the machining velocity on the generated forces, different crystallographic orientations have been chosen. Figure 1 shows the variation in the normal force with a change in the machining velocity at a 150 nm depth of cut. It was shown that there was not enough variation in the generation of the normal forces due to the variation of the machining velocities, however; the largest normal forces were observed at 333nm/s machining velocity.
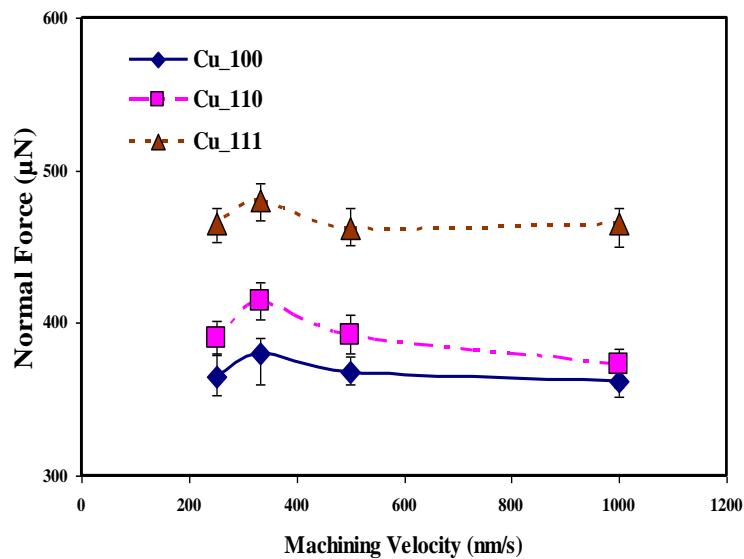
Figure 1: Variation in the normal force with change in machining velocity at 150 nm depth of cut on single crystal copper of (100), (110) and (111) planes.

Beyond this velocity, the generated normal forces decreased and remained constant with a further increase in the machining velocity. These results also showed that the generated normal forces were higher when machining was performed on the Cu (111) plane than on the Cu (100) and Cu (110) planes. This result is also consistent with the results [12] when the depth of cut was the variable parameter to measure the generated forces.
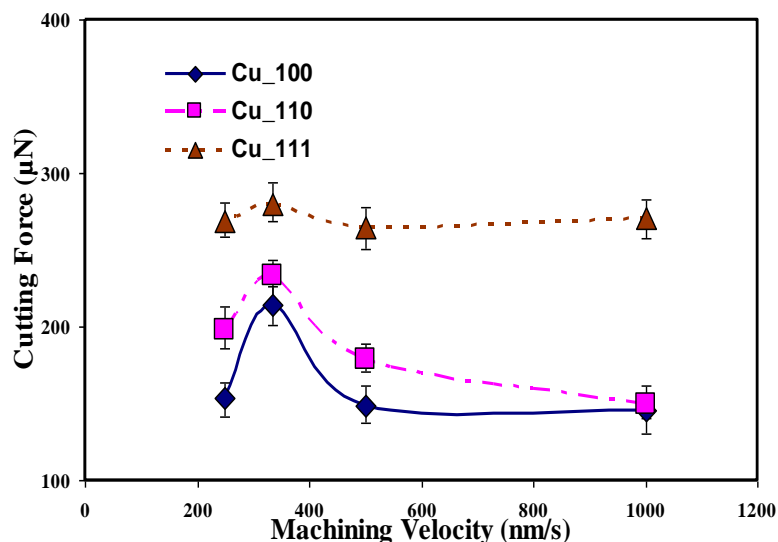

Figure 2: Variation in the cutting force with change in machining velocity at 150 nm depth of cut on single crystal copper of (100), (110) and (111) planes.

Figure 2 shows the variation in the generated cutting forces with the change in the machining velocity on different crystallographic orientations at a 150 nm depth of cut. It was observed that the trend of the generated cutting forces were similar to the obtained normal forces. Furthermore, the generated cutting forces were larger when machining was performed on the Cu (111) plane than that

of other crystallographic orientations. The normal and cutting forces data showed that both normal and cutting forces were higher in the Cu (111) plane than that in other planes; therefore it reveals that the Cu (111) plane is harder than the Cu (110) and Cu (111) planes.
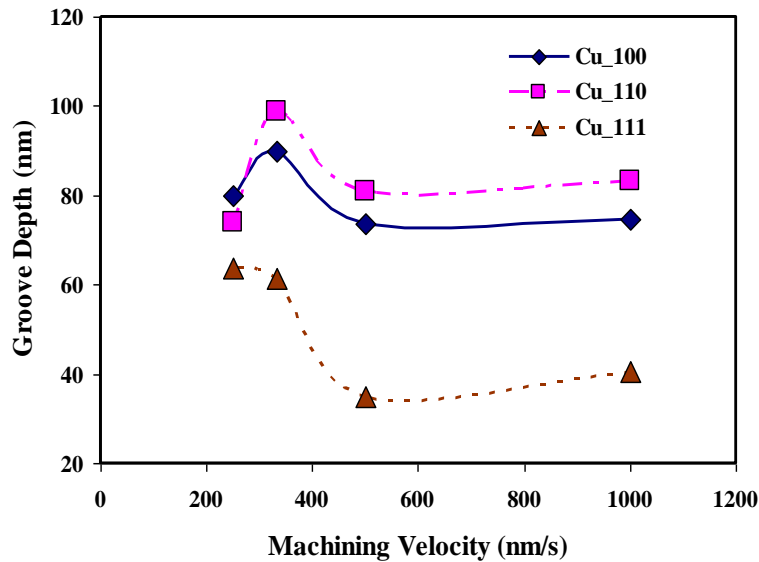

Figure 3: Variation in the obtained groove depth with the machining velocity at 150 nm depth of cut on single crystal copper of (100), (110) and (111) planes.
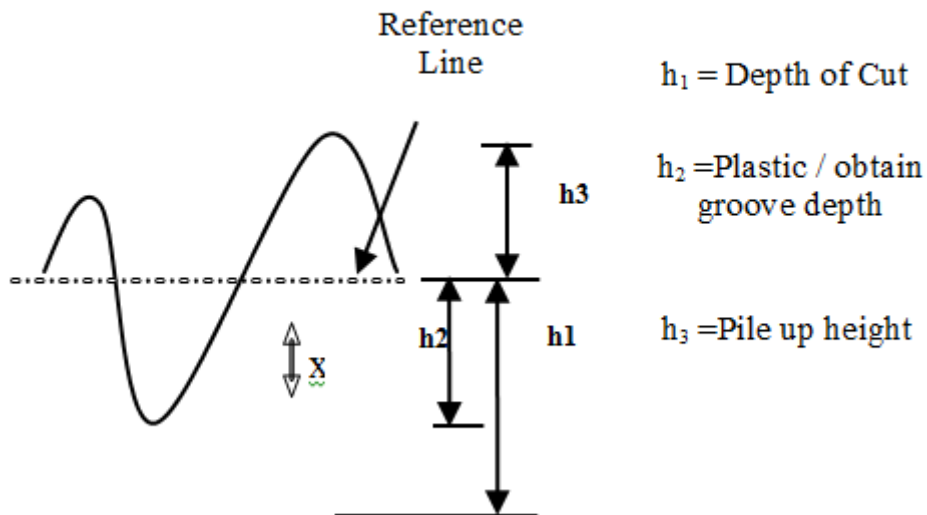

Figure 4: Schematic diagram of the machined profile.

To determine the elastic recovery at different machining velocities, the obtained groove depths were measured. Figure 3 shows the variation in the obtained groove depth with a change in the machining velocity at 150 nm depth of cut. The obtained groove depth increased from 250 to 333 nm/s machining velocity at 150 nm depth of cut. Above a machining velocity of 333nm/s, the groove depths decreased and remained almost constant with a further increase of the machining velocities. The obtained groove depths were larger when machining was performed on the Cu (110) plane than that on

the Cu (100) and Cu (111) planes at different machining velocities. The generated forces were higher and obtained depth value were lower on Cu (111) plane than the other planes and this result also reveal that the hardness of the Cu (111) plane is higher than that of other planes due to the higher atomic density of the Cu (111) plane.
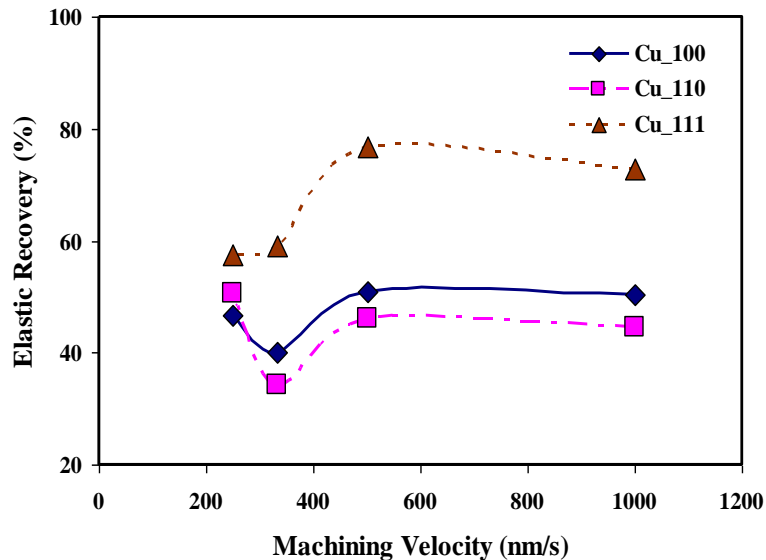

Figure 5: Variation in the elastic recovery with change in machining velocity at 150 nm depth of cut on single crystal copper of (100),(110) and (111) planes.

These obtained depth values were utilized to calculate the percentage of elastic recovery using the following expression:

$$\text{Elastic Recovery}\,(\%) = \frac{h_1 - h_2}{h_1} \times 100$$

The details of h_1 and h_2 were described in Figure 4.

Figure 5 shows the variation in the elastic recovery (%) with a change in the machining velocity at 150 nm depth of cut. The elastic recovery decreased from 250 to 333 nm/s machining velocity. From a 333 nm/s machining velocity, the value of elastic recovery increased and remained constant with the further increase of the machining velocities. As before, the percentage value of elastic recovery was inversed to the obtained groove depth. Therefore, the higher value of elastic recovery was observed on the machining of the Cu (111) plane by comparison to the other crystallographic orientations. These percentage values reveal that after a single scratching operation the primary deformation behaviour for these three crystal orientations were relatively highly elastic in nature. Moreover, the pile up were observed along the scratched profile after the machining operations and shown in Figure 6. These Pile up occurred due to the plastic deformation of the material. Therefore, this non-traditional nano scale machining condition responses to the percentage of elastic recovery and pile up for these materials indicate the mode of elastoplastic deformation mechanism as opposed to fully plastic deformation characteristics for the traditional machining operation.
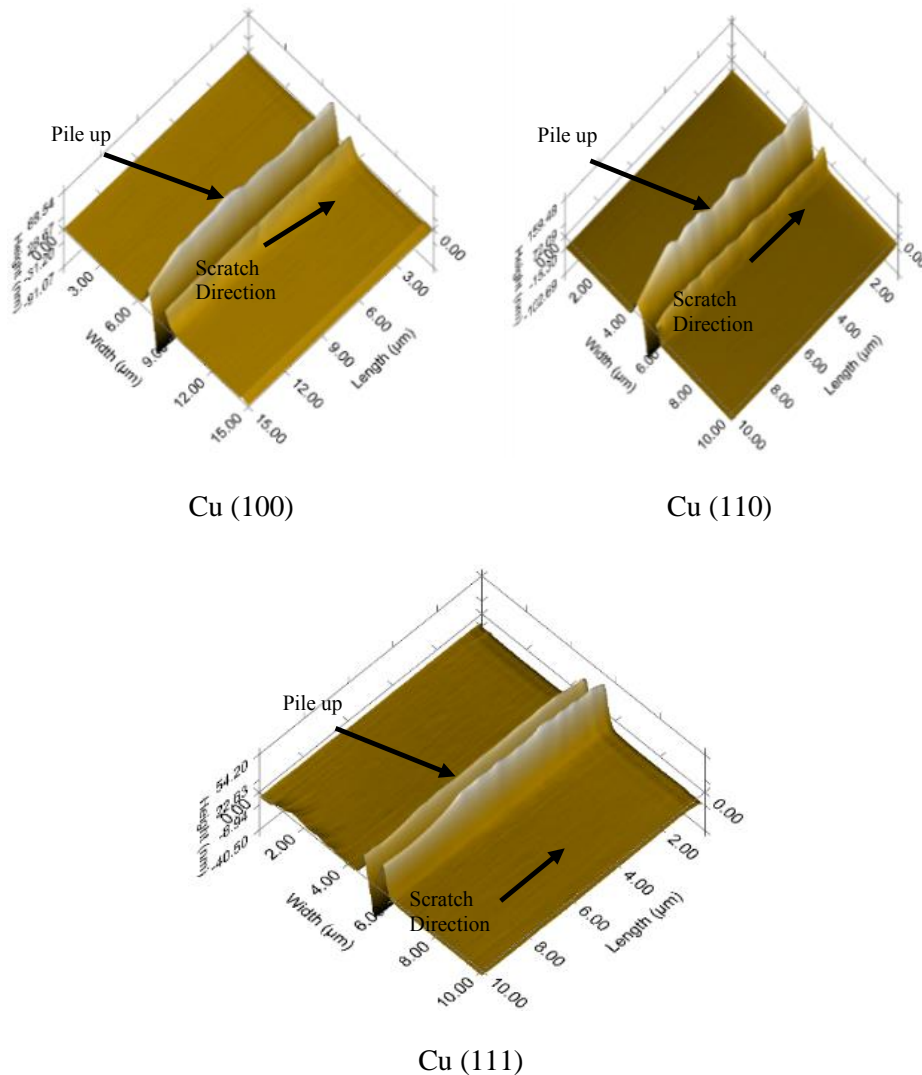
Figure 6: AFM-3D view of the machined surface morphology of the Cu single crystal after nano machining at the 150 nm depth of cut and 333nm/s machining velocity.

4. Conclusion

In this research, nano machining was performed on single crystal copper materials in different orientations. It was found that the largest amounts of normal and cutting forces were generated at 333 nm/s machining velocity. Beyond this velocity, both normal and cutting forces were decreased with a further increase in the machining velocity for Cu (100), (110), and (111) planes. The obtained groove depth was larger when machining was performed on the Cu (110) plane than the Cu (111) and Cu (100) planes at 333nm/s machining velocity. Therefore elastic recovery (%) of the crystal orientation was lower than the other two crystal orientations. Therefore, 333nm/s machining velocity can be the recommended velocity to do such type of nano machining operations.

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