Research on subsurface deformed layer in ultra-precision cutting of single crystal copper by focused ion beam etching method

Y Chen¹, X J Huang¹ and J X Kong¹
¹ Institute of Mechanical Manufacturing Technology, China Academy of Engineering Physics, 64 Mianshan Road, Mianyang, CHINA
E-mail: chen_yioh@sina.cn

Abstract. In this paper, the focused ion beam was used to study the subsurface deformed layer of single crystal copper caused by the nanoscale single-point diamond fly cutting, and the possibility of using nanometer ultra-precision cutting to remove the larger deformation layer caused by traditional rough cutting process was explored. The maximum cutting thickness of single-point diamond cutting was about 146 nm, and the surface of the single-crystal copper after cutting was etched and observed by using the focused ion beam method. It was found that the morphology of the near-surface layer and the intermediate layer of the copper material were larger differences: the near-surface of the material was smaller and more compact, and the intermediate material layer of the material was more coarse sparse. The results showed that the traditional precision cutting would residual significant subsurface deformed layer and the thickness was on micron level. Even more, the subsurface deformed layer was obviously removed from about 12μm to 5μm after single-point diamond fly cutting in this paper. This paper proved that the large-scale subsurface deformed layer caused by traditional cutting process could be removed by nanometer ultra-precision cutting. It was of great significance to further establish the method that control of the deformation of weak rigid components by reducing the depth of the subsurface deformed layers.

1. Introduction
Weak rigid components, which required high accuracy, were widely used in aerospace and other industries [1-3]. So far, the deformation of the weak rigid components was difficult to control due to the residual stress [4]. And the stress injury caused by residual stress was the main factor to form the subsurface deformed layers [5]. So, it was one of the most effective methods to study the deformation mechanism and control method of weak rigid components by studying subsurface deformed layers.

The depth of subsurface deformed layers was an important parameter affecting the quality of manufacturing quality. Nowadays, the measurements of the depth of subsurface deformed layers mostly were studied by computer simulation, which was proved to be a kind of useful method [6-10]. Verified by the molecular dynamics simulation method, Luo et al. reported that the use of nanoscale diamond tools to produce nanostructures results in the transferability of shapes [11]. Uezakia et al. used a method of local compressive stress to successfully suppress the plastic flow of material and improve the surface quality of the product [12]. Fang
et al. used molecular dynamics to study the phase transition of germanium during the nano-
cutting process [13].

Compared with the results obtained by the simulation method, although there were some
researchers using direct experimental methods, such as transmission electron microscopy
(TEM) [14][15], X-ray diffraction [16][17], Raman scattering [18], to study subsurface
metamorphic layers. However, there was still no validated experimental method to observe
the subsurface deformed layer during nano-cutting process. For manufacturing engineers,
finding the optimum machining parameters that produce minimum subsurface deformed
layers in materials, especially in metal materials, remained a difficult issue.

In this paper, the focused ion beam (FIB) method was used to study the subsurface
deformed layer of single crystal copper caused by the traditional precision cutting and the
nanoscale single-point diamond fly cutting. The possibility of using nanometer ultra-precision
cutting to remove the larger deformation layer caused by traditional precision cutting process
was discussed.

2. Materials and Methods
The material used in this paper was commercial pure single crystal copper. The pure copper was first
processed by cold forging method at room temperature, and then, combined with 400 °C ×8-hour
annealing, the grain size of the pure copper material will be reduced to about 10~20 μm.

The fine grain size copper samples were first rough cut using a precision machining machine. Then,
it was cut by a homemade ultra-precision single-point diamond fly cutting machine. The fly-cutting
machine used an air-bearing tooling spindles and a hydrostatic support rail which driven by a linear
motor. A single-point diamond tools with a radius of 5 mm were used to cut the pure copper on fly-
cutting machine.

The main process parameters of ultra-precision cutting were shown in Table 1.

| Table 1. the main process parameters of ultra-precision cutting |
|---------------------------------------------------------------|
| Depth of cut | Speed of horizontal rail | Spindle speed |
| $a_p$ | $v$ | $\omega$ |
| 3 μm | 12 mm/min | 280 r/min |

The principle of single-point diamond flying cut process was shown in figure 1. The
parameter $R$, equal to 5 mm, represents the radius of the diamond tool. The parameter $f$, equal
to $V/\omega$, was the cutting feed in horizontal direction.

Figure 1. Principle of single-point diamond flying cut
As shown in the figure 1, the center of the diamond tool moved from C to C’ after a single feed. The parameter $h_{\text{max}}$, represented the maximum cutting thickness of flying cut, can be calculated by the formula (1) as follow.

$$h_{\text{max}} = R - \sqrt{R^2 + f^2 - 2f\sqrt{2Ra_p - a_p^2}}$$

(1)

Through the parameters of fly-cutting process used in this paper, the maximum cutting thickness of flying cut can be calculated by formula (1) as 146 nm. Therefore, the thickness of ultra-precision cutting process in this paper was on the nanometer scale.

After the two times of the single point diamond fly cutting process, one side of the pure copper sample’s surface were processed to the mirror as shown in figure 2. The surface roughness of the pure copper was measured at about 80 nm using a dynamic interferometer.

The FIB (focused ion beam) method was used to etch the surface of the material and observe the subsurface deformed layer in situ after the copper sample’s cutting. The FIB used in this paper had a gallium ion source. When high energy gallium ions collided with the samples, they sputter the atoms from the surface and remove the material. Therefore, the FIB method was used as a micro processing tool in this paper. The etching process was direct etching without auxiliary gas. As figure 3 shown, a small piece of copper sample was sampled by wire cutting and placed into the FIB chamber for etching.

3. Results and Discussion

The material morphology of the pure copper surface after ultra-precision cutting and FIB etching was shown in figure 4. The FIB etching was using oblique etching method. The initial location of the FIB etch was located at the long side of the trapezoid (about 60 μm) in the figure. From the initial position, the etching depth would gradually increase. Through the process optimization, the final etching depth of the copper, located at the short side of the trapezoid (about 12 μm) in the figure, was about 20 μm by adjusting the etching time.
The subsurface material morphology was observed in-situ along the Z direction. It could be found that there was a big difference between the material morphology of the pure copper material near the surface layer and the intermediate layer. Due to the role of pre-forging and heat treatment, the material grain size of intermediate layer was about 15\(\mu\)m. The grain size conforms to the experience.

The morphology of material near the surface changed after the cutting process. Obviously, the submicron level. This shows that the properties of near-surface pure copper materials had changed, forming a subsurface deformed layer. On the other hand, according to the tilt angle of the sample during the etching of the FIB, the depth of the subsurface deformed layer of the pure copper, obtained through geometric conversion and measured by the calibrated FIB algorithm, was about 5 \(\mu\)m.

The near-surface materials were further etched in order to determine whether the changes in the near-surface material were caused by the gallium ion sputter of the FIB. In this etching process, the pure copper sample was first etched down overall about 20 microns. Then, on the inner material, the pure copper material was removed obliquely using the etching method. The etch results shown in Figure 5.

Figure 4. View of the near-surface and the intermediate material layer of the etched copper
As shown on figure 5, no smaller and more compact grains of the material were found. The results indicated that the smaller and more compact material deformed layer existed only on the near surface of the material and was not caused by gallium ion sputtering of FIB. Therefore, the subsurface deformed layer of pure copper in this paper was caused by the mechanical and thermal effects of cutting. This result was consistent with the findings of other scholars.

In order to identify whether the deformed layer was formed by rough cutting or ultra-precision cutting, FIB etching was performed on the other side (backside) of the pure copper sample that had not undergone single point diamond fly-cutting process. The etching result was shown as figure 6.

The subsurface deformed layer near the surface of no ultra-precision machined pure copper material was also found in the figure 5. And on this time, the depth of the subsurface deformed layer, also measured by the calibrated FIB algorithm, was about 12 μm. Therefore, the rough cutting process would surely course the subsurface deformed layer.

Compared with the depth of subsurface deformed layer after ultra-precision cutting process, which was 5 μm, the depth of the subsurface deformed layer without ultra-precision fly
cutting process was larger. The difference between the two depths was approximately equal to the sum of the depths of the two ultra-precision fly cutting processes \(2a_p = 6 \mu m\). Furthermore, it could be found that the morphology and size of the subsurface deformed layer’s grain in the two experiments were basically the same. Therefore, the subsurface deformed layer found in this paper was mainly caused by rough cutting, while the nanoscale ultra-precision cutting process could accurately remove them.

4. Conclusions

In this paper, the focused ion beam was used to study the subsurface deformed layer of single crystal copper caused by the nanoscale single-point diamond fly cutting. By etching the rough cutting surface and the ultra-precision cutting surface of the pure copper material respectively, the following conclusions could be drawn:

(1) The subsurface deformed layer of single-crystal copper was mostly formed by rough cutting. The grain of subsurface deformed layer material was smaller and more compact, whose scale was in the sub-micron level.

(2) It had been proved that the nanoscale single point diamond fly cutting process could obviously reduce the subsurface deformed layer formed in the previous rough cutting process. The subsurface deformed layer caused by nanoscale fly cutting was not significant. This result provides a basis for the design and optimization of ultra-precision cutting processes.

The paper proves that the large-scale subsurface deformed layer caused by traditional rough cutting process could be removed by nanoscale ultra-precision cutting. The research results were instructive for the machining of materials sensitive to subsurface damage. At the same time, it was of great significance to further establish the method that control of the deformation of weak rigid components by reducing the depth of the subsurface deformed layers.

Acknowledgments

Supported by Science Challenge Project, No. JCKY2016212A506-0107.

References

[1] Huang P L, Li J F, Sun J and Jia X M 2016 Int. J. Adv. Manuf. Tech. 84 2461-69.
[2] Wu Q, Li D P, Ren L and Mo S 2016 Int. J. Adv. Manuf. Tech. 85 1291-1302.
[3] Ezugwu E O 2005 Int. J. Mach. Tool Manu. 45 1353-67.
[4] Hu Y, Yang R, Wang D and Yao Z 2018 J. Mater Process Tech. 251 197-204.
[5] Wang Q, Bai Q, Chen J, Sun Y, Guo Y and Liang Y 2015 Appl. Surf. Sci. 344 38-46.
[6] Maiti R, Gerhardt L C, Lee Z S, Byers R A, Woods D, Sanz-Herrera J A and Carrè M J 2016 J. Mech. Behav. Biomed. 62 556-69.
[7] Zhao H, Shi C, Zhang P, Zhang L, Huang H and Yan J 2012 Appl. Surf. Sci. 259 66-71.
[8] Lai M, Zhang X and Fang F 2013 Nanoscale res. lett. 8 353.
[9] Tarasov S, Rubtsov V and Kolubaev A 2010 Wear 268 59-66.
[10] Outeiro J C, Campocasso S, Denguir L A, Fromentin G, Vignal V and Poulachon G 2015 CIRP Ann-Manuf. Techn. 64 53-6.
[11] Luo X, Tong Z and Liang Y 2014 Appl. Surf. Sci. 321 495-502.
[12] Uezaki K, Shimizu J and Zhou L 2014 Precis. Eng. 38 371-8.
[13] Lai M, Zhang X, Fang F, Wang Y, Feng M and Tian W 2013 Nanoscale res. lett. 8 13.
[14] Yan J, Asami T, Harada H and Kuriyagawa T 2012 CIRP Ann-Manuf. Techn. 61 131-4.
[15] M'Saoubi R, Larsson T, Outeiro J, Guo Y, Suslov S, Saldana C and Chandrasekar S 2012 CIRP Ann-Manuf. Techn. 61 99-102.
[16] Tanaka H, Shimada S and Anthony L 2007 CIRP Ann-Manuf. Techn. 56 53-6.
[17] Mahmoodi M, Sedighi M and Tanner D A 2012 Mater Design 40 516-20.
[18] Conti C, Colombo C, Realini M, Zerbi G and Matousek P 2014 Appl. spectrosc. 68 686-91.