A Simulation Study on the Effect Factors of Oxygen-free Copper During Nano-micro Scratching Tests

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Abstract. With the development of materials science and technology, industry demand for increasingly high performance materials. In recent years, the research on the friction and wear characteristics of materials has become a research hotspot as one of the most important factors of service performance. In this paper, a study of oxygen-free copper in micro-scratching process using smooth particle hydrodynamic method is taken to study the micro-mechanical properties of materials. It also has important significance for the micro-groove processing mechanism and material processability study.

1. Introduction

In recent years, the research on the friction and wear characteristics of materials has become a research hotspot as one of the most important factors of service performance [1,2]. Scratching test as a high-resolution test method not only helps to analyze the micro-mechanical properties of materials, but also has important significance for the micro-groove processing mechanism and material processability study.

The scratch test method can measure mechanical parameters such as friction coefficient, scratch resistance and dynamic scratch hardness on the surface of a material, and can also solve problems such as processability and optimization of process parameters in the cutting process. Therefore, it is widely used in many fields. It is commonly used in testing and analysis of mechanical properties of various materials such as films and coatings. In recent years, the scratch method has been rapidly developed in terms of theory, instrument research and development, and application. The requirements for instrument accuracy and test factors are also getting higher and higher. However, the scratch test process is more complicated and unavoidably affected by many factors during the test process. Such as the vertical factors caused by mechanical assembly, the contact depth error due to material protrusions or recesses, etc. Therefore, it is necessary to carry out analytical work on the influencing factors of the scratch process [3,4].

In order to represent the friction and wear property of the material more accurately, we need to judge the machinability of the material and analyze the microscopic mechanical behavior of the material and guide the precision machining process. In this paper, smooth particle dynamics (SPH) method is used to simulate the scratch process of oxygen-free copper, and the influences of contact depth, scratch rate and non-vertical factors on the stress state and scratch process of the material under different process parameters are studied.
2. Indenter Analysis and Model Establishment

2.1. Cone Indenter

The main process of scratch measurement is to apply a certain normal load on the tough tip with a small radius and proceed to scratch measurement along the sample surface. The friction and wear mechanism of the material is studied by recording the scratching load, contact depth and groove width of the surface. The shape of the indenter includes sharp, cambered and flat. Sharp tips include three-pyramid indenter, four-pyramid indenter, cone indenter and so on. Due to the limited processing technology during machining the tip, it is difficult to achieve the ideal part. Generally, the radius of the arc is at the nanometer level, which will cause great error in the indentation test at a small scale. Axisymmetric character makes it widely used in scratching tests rather than indentation tests [5].

2.2. Conical Indenter Model

The projection area of the ideal conical indenter in the \(x-y\) plane is a circular. When the cone indenter is perpendicular to the specimen, the contact depth is \(h_c\) and the half-cone angle is \(\beta\), the projected area can be calculated as

\[
A_{\text{proj}} = \pi h_c^2 \tan^2 \beta
\]  

(1)

When the indenter axis is at an angle of \(\theta\) with the specimen, the projection of the cone on the horizontal \(x-y\) plane is an ellipse as shown in figure 1 [6]. The elliptic equation for the projection region is as following:

\[
\left(\frac{x + \frac{h_c \tan \theta \tan^2 \beta}{1 - \tan^2 \theta \tan^2 \beta}}{h_c \tan \theta \tan^2 \beta \left(1 - \tan^2 \theta \tan^2 \beta\right)}\right)^2 + \left(\frac{y}{h_c \tan \theta \tan^2 \beta \left(1 - \tan^2 \theta \tan^2 \beta\right)}\right)^2 = 1
\]

(2)

The ellipse equation shows that the center of the ellipse does not coincide with the central axis of the cone indenter. The area of the projected ellipse region can be expressed as following:

\[
A_{\text{proj}} = \pi ab = \pi h_c^2 \tan^2 \beta \left(1 - \tan^2 \theta \tan^2 \beta\right)
\]

(3)

When the cone indenter has a half-cone angle of 60°, the contact depth is 1μm, 2μm and 3μm respectively, the percentage error is shown in figure 2 with different tilt angle of \(\theta\).

![Figure 1. Projection diagram of cone indenter.](image-url)
According to the percentage error curve, the larger the cone angle of the indenter is, the greater the error will be in the same tilt state. This is due to the larger cone angle of the indenter and the specimen surface contact width. Moreover, the increase of tilt angle will lead to the increasing of error for the same cone angle. We can clearly see that the error percentage is independent of contact depth.

3. Establishment and Analysis of Simulation Model

3.1. Simulation Model
In this paper, the influence of parameters on micro/nano scratch process are discussed. The size of simulation model is $3\mu m \times 12\mu m \times 4\mu m$ in $x, y, z$ directions considering calculation amount and accuracy. The total number of particles is 288,000 with a diameter of 100nm. The model is shown in figure 3. In the simulation process, the material is set to be isotropic and uniformly distributed, regardless of its own defects and lattice factors. The overall 6 degrees of freedom of specimen on the bottom and right side are fixed. The specimen’s front side and back side are fixed through defining two symmetry planes. Diamond material is chosen to made indenter and the cone angle is 120°. Sample material is Oxygen-free copper which is widely used. Johnson-cook material model is used to describe the stress-strain relationship in the testing process [7].

Figure 2. Percentage error graph of cone indenter

Figure 3. Scratching model:(a) schematic diagram, (b) micro-scratch model and (c) section view
3.2. Effect of Contact Depth

Figure 4, 5 and 6 are section, top views and comparison graphs of mechanical curves in speed of 100nm/s with 7μm scratching distance. The unit of stress is GPa. We can clearly see that residual stress on the surface of the groove and the I II and III stress areas also increased obviously with the increase of the depth. The contact area between the tip and the matrix material increases, the material being extruded and also the plastic flowing resulting from plastic deformation increase during the movement of the indenter. These factors due to materials accumulated in the head of indenter. The plastic deformation of the material on both sides of the groove intensifies the extrusion of the matrix material, resulting in the increase of the residual stress region. In figure 6, the normal and tangential force increase significantly with the increase of scratch depth. It is because that the contact area between the tip and specimen increases. And the interaction between them increases with the increase of the scratch depth simultaneously. The friction coefficient fluctuates obviously when the contact depth is 100nm. However, it displays stable when the depth is 200nm and 300nm. We can conclude that cone indenter is not suitable for small scale scratching processing.

Figure 4. Section views of different contact depth

Figure 5. Top views of different contact depth
3.3. Effect of Velocity
Figure 7, 8 and 9 are section, top views and comparison graphs of mechanical curves in contact depth of 200nm with 7μm scratching distance. It is clearly shown that there’s no obvious variation between the deformation region and material overflow height. In top views, all grooves width are 1.1μm. Similar to the stress distribution, the scratch velocity has little influence on the mechanical response of the scratch process of conical indenter shown in figure 9.

Figure 6. Mechanics curves of different contact depth

Figure 7. Section views in different scratching velocity

Figure 8. Top views in different velocity
3.4. Effect of Tilt Angle

Figure 10, 11 and 12 are section, top views and comparison graphs of mechanical curves in contact depth of 200nm, in speed of 100mm/s with 7μm scratching distance. When the tilt angle of the tip is 3° and 5°, not only the distribution of stress and strain on the surface and subsurface of the material does not change, but also the width of the groove. From the top view, the residual morphology showed that the groove width is 1.4μm when the tilt angle reached 10°, which increased by 27% compared with the vertical scratch groove. It can be seen from the figure 12 that the normal and tangential loads change little under the conditions of 3° and 5°. The two loads increase slightly when the tilt angle reaches 10°, which is caused by the increase of the horizontal projection of the contact area and the expansion of the extrusion area on the material.
4. Conclusion
Using the SPH method, the effect of factors on the scratched surface topography, subsurface layer, and scratching force are investigated. The conclusions can be drawn: The contact depth has a great influence on the plastic deformation of the material. A small contact depth will cause the friction coefficient to fluctuate sharply. Therefore, the conical tip is not suitable for machining at a small scale. The scratch speed has no obvious influence on the surface, groove morphology and mechanical response of the material. The non-vertical state has no effect on the distribution of stress and strain on the material surface and subsurface, but has a detailed effect on groove width and mechanical response.

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