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The effect of Berkovich tip orientations on friction coefficient in nanoscratch testing of metals

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ABSTRACT

In this paper, an analytical model is established to calculate both the ploughing and adhesive friction coefficients of metals in a scratch test with the Berkovich indenters at different tip orientations. Using the finite element analysis of nanoscratch test, the patterns of material flow lines around the indenter at different tip orientations are extracted. The adhesive friction coefficient is predicted based on the average angle of material flow lines along each side of the contact surface. When the scratch direction is between the edge-forward and side-forward orientations, the material pile-up in front of the indenter becomes unbalanced between the area of two sides of the contact surface and it highly affects the ploughing friction coefficient.

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1. Introduction

Nanoindentation and nanoscratch tests are widely used to investigate the wear and tribology properties of bulk materials, coatings, thin films, MEMS and etc. Nanoscratch and microscratch tests are generally done using conical indenters. However, for many cases, researchers use pyramidal indenters to do scratch tests and investigate the surface tribology. Nanoscratch testing with a Berkovich indenter is generally performed using three different tip orientations: the edge-forward, face-forward and side-forward [1–5]. Face and edge-forward orientations of scratching can be easily done by reversing the scratch direction. Generally to perform different nanoindentation or nanoscratch tests on different materials, different indenters are installed. Sometimes the replacement of indenters accompanies with errors. There is often a mismatch between the desired and actual installation orientations due to difficulties in orientating the tip exactly in the favorable way. Therefore, it is necessary to investigate the nanoscratch behavior of the Berkovich indenter for different tip orientations.

The material deformation, pile-up formation in front of the indenter and apparent friction coefficient, μ_{app}, in the ploughing scratch with a pyramidal indenter depend on the scratch orientation [5]. Mulliah et al. [6,7] accomplished a molecular dynamics (MD) simulation of nanoscratch testing of FCC silver (100) surface using a pyramid indenter. They carried out the MD simulation for the face, side and edge-forward orientations of the indenter. They could demonstrate that the scratch groove and apparent friction coefficient vary with the tip orientation. Shi et al. [8] studied the effect of indenter tilt and its rotation around all three axes for the edge-forward scratch on the residual scratch groove and apparent friction coefficient. They studied the effect of indenter rotation in the range of $\pm 5°$ relative to the edge-forward scratch using a finite element simulation. They concluded that, the indenter rotation in the mentioned range will cause only slight changes in the apparent friction coefficient. Youn and Kang [9] investigated the effect of three different orientations of the Berkovich tip on the apparent friction coefficient of the single-crystal silicon through the nanoscratch with 20 wt% KOH-etching tests. They found that the tip orientation has a significant influence on the apparent friction coefficient which varies from 0.16 to 0.38. Bakshi et al. [10] suggested a method to compute the contact and true wear volume which takes into account different orientations of the Berkovich tip.

The adhesive friction coefficient, μ_a, is an amount of the friction coefficient produced by the frictional shear force in the contact surface. Considering that the direction of interfacial frictional shear stress vector on each element of the contact surface can be different from the scratch direction, thus, the adhesive friction coefficient is not necessarily identical to the local friction coefficient. The direction of the interfacial shear stress vector is corresponding to the direction of the material flow line at the interface.

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Thus, to calculate the adhesive friction coefficient it is necessary that the direction of relative displacement vector between the indenter and material at each point of the contact surface be known, that is so-called material flow lines. Different assumptions were provided by researchers regarding the material flow lines around the indenter or surface asperities. Two methods of the slip line theory [11–14] and the upper bound method [15–17] were developed and utilized by many researchers in order to determine the adhesive friction coefficient and deformation of the material, and to describe the material flow lines around the indenter with a known geometry such as pyramid, conical and spherical shapes.

Goddard and Wilman [18] developed an analytical model to calculate the friction coefficient of the three-sided pyramidal asperities for different scratch directions. They assumed that the material flow lines are in horizontal planes, which are parallel to the scratch direction. They also assumed that for $0^\circ < \varphi < 30^\circ$ (Fig. 1b), the areas of the left and right sides of contact surface are identical. Tayebi et al. [19] extended the analytical model developed by Goddard and Wilman [18] for spherical asperities. They assumed an inclined angle of the material flow lines along the contact surface. Jardret et al. [20] assumed that the material flow lines orient at a constant angle relative to the scratch direction of the Berkovich indenter in the edge-forward orientation. Subhash and Zhang [21] assumed that the material flow lines around a conical indenter are as inclined lines relative to the vertical axis and then they established an analytical model to calculate the apparent friction coefficient for a conical indenter in the ploughing scratch. Lafaye et al. [22] proposed a flow-line model for the ploughing scratch produced by a conical indenter based on the true contact area. Three types of flow-line model were proposed by them including horizontal lines, vertical lines and an intermediate case. Linde et al. [23] assumed that the flow lines should be in a way that have minimum deviation from the far field velocity vector of material. Thus, the flow lines should have the maximum projection magnitude along the scratch moving vector.

In this paper, an analytical model is established to calculate both the ploughing and adhesive friction coefficients of metals in a scratch test by the Berkovich indenter at different tip orientations. To investigate the effect of tip orientation on the material flow lines along the contact surface as well as the pile-up formation in front of the indenter, the finite element (FE) analysis of the nanoscratch test is carried out. The results of the FE analysis are validated using the experimental results of the nanoscratch test performed on the ferrite phase of ductile cast iron specimen. Considering the material pile-up in front of the indenter, the real contact area is estimated and the ploughing friction coefficient is calculated. By tracking the trajectory of the material points on the surface of specimen, the material flow lines around the indenter are calculated for different Berkovich tip orientations. The adhesive friction coefficient is calculated based on the direction of the material flow lines along the contact surface. Finally, the apparent friction coefficients for different Berkovich tip orientations are calculated.

2. Material and experiments

Different scratch orientations of the Berkovich indenter are illustrated in Fig. 1a. The tip orientation or tip rotation angle is represented with the angle φ between the scratch direction and one of the indenter edges. Considering the geometrical symmetry of the Berkovich indenter, by changing the angle $0^\circ < \varphi < 60^\circ$ different orientations can be made by the Berkovich indenter.

To verify the FE analysis of nanoscratch testing and to investigate the effect of Berkovich tip orientations on the apparent friction coefficient, some nanoscratch tests by the Berkovich indenter in three different orientations were performed on the ferrite phase of ductile iron EN-GJS 400-18. To obtain a smooth surface for performing the nanoscratch test, all the specimens were grounded by 200–2000 grit SiC sandpapers and then polished with 1.0 and 0.1 μm diamond pastes. Before starting the nanoscratch test, the roughness of all specimens was measured using the scanning probe microscopy (SPM). The surface roughness after final polishing was < 4 nm. For each scratch direction, at least 6 nanoscratch tests with different normal loads were conducted.

The nanoscratch tests were performed using a Triboscope system (Hysitron Inc., USA). Furthermore, the local friction coefficient was measured using a diamond conical indenter with a cone angle of 90° and a tip radius of 5 μm. The measured local friction coefficient was about 0.053.

3. FE analysis of the nanoscratch test

Fig. 2 shows the FE mesh patterns used for simulating the specimen and Berkovich indenter in a nanoscratch test. It is assumed that the specimen or indenter is not tilted. For the tip rotation angles of $\varphi = 0^\circ$ and 60° (i.e. edge-forward and face-forward orientations respectively), because of the symmetry in the geometry and loading conditions, only one half of the geometry is taken into account and symmetric boundary conditions are employed across the symmetry plane. For the other tip orientations,

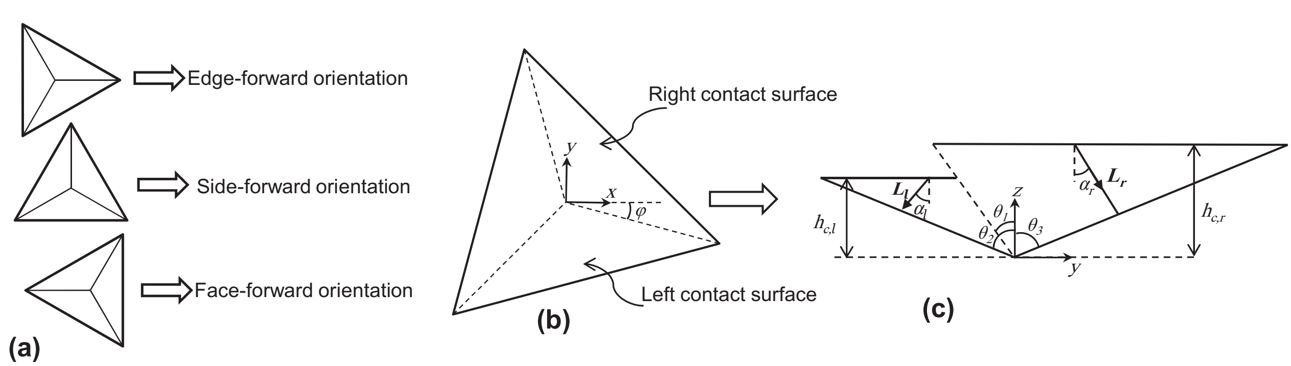

Fig. 1. Schematic representation of the Berkovich indenter: (a) different tip orientations, including edge-forward, side-forward and face-forward. (The indenters are viewed from top and scratch directions are shown by arrows), (b) definition of tip rotation angle φ (top- view of the indenter), and (c) definition of parameters related to flow lines for a Berkovich indenter (front-view of the indenter).

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