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Micro-characterization of macro-sliding wear for steel

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ABSTRACT

The wear behaviours of 65Mn and 40CrMnSiW steels were investigated by subjecting them to nanoscratch, nanoindentation, and dry sliding wear processes. A simple modified equation for calculating nanoscratch true wear volumes is developed, i.e. the true volumes are closely related to the elastic recovery angle which can be given easily. When comparing the nanoscratch phenomena with macro sliding wear, it was found that the micromechanism of the macro wear was similar to those of nanoscratching. The nanoscratching and the macro sliding wear testing represented the procedures for evaluation of single-asperity and multi-asperity contact behaviours of abrasive wear, respectively. In addition, to compare wear resistance properties of steels, the mean wear rate increased with decreases in ratio of the hardness H and the reduced modulus E_r in turn, namely, the value of H/E_r can help to assess the wear resistance of steels in some degree.

1. Introduction

Wear is a common phenomenon in industry, which has been considered to be the main failure form of machine parts. According to statistics [1,2], the consumption of energy and materials due to the wear of various mechanical steel parts is enormous. Thus scientists and engineers have paid more and more attention to the problem of wear and have carried out active investigations of the tribological properties of steels, hoping to improve the wear resistance of materials in order to extend service lifetime and reduce economic losses.

The wear phenomena of steels are very complex, involving many factors, such as counterpart, load, temperature, speed of the interacting machine components, surface roughness, and so on. In addition, wear mechanisms include abrasion, adhesion, plastic deformation, oxidation, delamination, and fatigue in practical applications as well as in laboratory investigations. To overcome the complexity and understand the nature of wear problems, many investigators have searched for simple methods of characterizing micro wear mechanisms of macro wear phenomena.

At present, one of the basic approaches to evaluating the tribological properties of steels is to subject them to dry sliding wear, which is considered to constitute an evaluation procedure for simulating multi-asperity contact behaviour of abrasive wear with SiC sandpaper as friction pairs. In the last decade, with the rapid development of nanotechnology and the advent of the TriboIndenter In-Situ Nanomechanical Test System, the nanoscratch method, which is considered a simple technique for assessing single-asperity contact behaviour of abrasive wear of materials at nanoscale, has been widely applied to measure the wear properties of polymers [3,4], polymer composites [5,6], ceramics [7,8], metals [9–13], metal composites [14,15], amorphous alloys [16,17], and electronic materials [18,19]. However, very few of the reported investigations have focused on the wear behaviours and micro-characterization for macro-sliding wear of steels via the nanoscratch technique.

In this study, the wear behaviours of steels were investigated by subjecting them to nanoscratch, nanoindentation, and dry sliding wear processes. The aims of the study were: (i) to establish a simple modified equation for calculating the

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true wear volume that was scratched; and (ii) to find internal relationship between nanoscratch and macro-sliding wear for steel.

2. Experimental

2.1. Materials

The 65Mn and 40CrMnSiW steels used in this study were prepared by vacuum melting and then subjected to forging treatment with a forging ratio of 7.2. The chemical compositions of the steels are tabulated in Table 1. Four specimens were prepared as presented in Table 2 and were labelled as Nos. 1 to 4, respectively. The two samples of 65Mn were austenitized at 860 °C for 1.5 h, followed by quenching in water and water quenching plus tempering at 200 °C for 2 h, respectively. The two samples of 40CrMnSiW were austenitized at 860 °C for 1.5 h and then quenched in water or oil, respectively. Cubes of 10 × 10 × 10 mm were cut from the treated samples and were then polished and ground using 2.5 μm diamond paste, followed by polishing on precision lapping (UNIPO-802) using 1 μm diamond paste to give the samples a controlled mean surface roughness value (*Ra*) of 2 nm.

2.2. Nanoindentation and Nanoscratch Tests

Prior to nanoscratch and nanoindentation tests, sample surfaces were cleaned with acetone and dried. Nanoindentation experiments on all samples were conducted using a Hysitron TriboIndenter with a diamond Berkovich indenter tip. The indentation cycle included three stages: loading for 10 s, holding for 10 s at a peak load, and unloading for 10 s. Nanoscratch tests were performed using a Hysitron TriboIndenter equipped with a two-dimensional (2D) force transducer to measure the vertical and lateral forces and a 120° conical probe with 3 μm radius of curvature coupled to an atomic force microscope (Nanoscope II, Digital Instruments). The scratches were performed at a constant load with a scratching speed of 0.33 μm/s and a total scratch length of 10 μm, and surface profiles before and after scratching were imaged by scanning probe microscopy (SPM) at the applied load of 2 μN. Each specimen was subjected to nanoindentation and nanoscratch tests at identical applied loads of 3000 μN and 5000 μN, respectively. The nanoindentation and nanoscratch experiments were carried out ten times to check the reproducibility under the same environmental conditions and then the mean values were obtained at different applied load conditions.

2.3. Sliding Wear Test

Dry sliding abrasion tests were carried out using two-body pin-on-disc wear test equipment (Model MMU-10G) at room temperature as shown in Fig. 1 under a load of 40 N and a rotation speed of 100 r/min. In order to eliminate the effect of three-body abrasive wear, the debris was blown away by electric fan during the experiment. Circular pins with a size of Φ 4 × 22 mm were machined out of the treated steels, then ground using 200, 400, 600, 800, 1000, and 1200 mesh sandpapers successively, and polished using 2.5 μm diamond paste. SiC abrasive papers of 150 grit were used on the discs during abrasion tests. The linear sliding velocity and contact pressure were calculated to be 0.125 m/s and 1.6 MPa, respectively. Before and after each test, the samples were weighed using an electronic scale with a resolution of 10^{-4} g. Each abrasion test was repeated three times and the results were averaged. Wear rates were calculated from weight loss. Worn surfaces of the steels were examined using a scanning electron microscope (KYKY2000), and three-dimensional (3D) wear surface topographies were determined using AFM (Solver P47).

Table 1 – Chemical compositions of experimental steels (wt.%).

	C	Si	Mn	Cr	Ni	W	P	S
65Mn	0.65	0.1	1.13	–	–	–	≤0.02	≤0.02
40CrMnSiW	0.39	1.80	1.79	1.78	0.41	0.9	≤0.02	≤0.02

Table 2 – Corresponding relationship between sample number and heat treatment processing.

Steel	Heat treatment processing	Sample
65Mn	Austenitizing at 860 °C for 1.5 h + water quenching	No. 1
	Austenitizing at 860 °C for 1.5 h + water quenching + tempering at 200 °C for 2 h	No. 2
40CrMnSiW	Austenitizing at 860 °C for 1.5 h + oil quenching	No. 3
	Austenitizing at 860 °C for 1.5 h + water quenching	No. 4

3. Results and Analysis

3.1. Nanoindentation

Olive and Pharr [20] have documented the theoretical relationship between the elastic modulus and the hardness by the depth-sensing indentation technique. In this technique the elastic modulus of the specimen is related to the measured reduced modulus E_r by:

$$\frac{1}{E_r} = \frac{1-v^2}{E} + \frac{1-v_i^2}{E_i} \quad (1)$$

where E_i and v_i are the elastic modulus and Poisson's ratio of the indenter, respectively, and E and v are the elastic modulus and Poisson's ratio of the specimen, respectively.

The hardness is defined as the peak load divided by the area of the indenter [20]:

$$H = \frac{P_m}{A}. \quad (2)$$

Fig. 2 shows the load-depth curves of four specimens at the applied loads of 3000 μN and 5000 μN. Based on the load-depth curves, the elastic modulus and the hardness were determined by the Olive and Pharr method. The mean values of H, E_r, and H/E_r are listed in Table 3.

In addition, during the nanoindentation experiment, h_f is the residual depth and h_{max} is the maximum depth, as shown