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Abrasive wear behavior of a pearlitic (0.4%C) steel microalloyed with vanadium

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Abstract

Abrasion induced subsurface deformation and work hardening along with related microstructural changes of the pearlitic (0.4%C) steel with vanadium additions has been examined. The abrasion testing was performed using a pin-abrasion apparatus in which a small pin of the specimen was ground on an abrasive paper at an applied load of 2.1 N and a sliding speed of 0.66 m/s. Crushed silica particles (size: 15–67 μm) were used as the abrasive medium. It has been found that the steel subjected to precipitation hardening of vanadium carbide exhibited higher wear rate than the vanadium free steel, although the bulk hardness by Vickers indenter of the microalloyed steel was higher than that of the vanadium free one. The nanohardness of the vanadium free steel increased with decreasing the contact depth below the abraded surface to about 2.1 times the original value, while the precipitation hardened steel to about 1.4 times. The varying nature of influence of interlamellar spacing and the vanadium addition on the wear response of the pearlitic steel has been discussed in terms of the differences in resistance to plastic deformation and especially the differences in energy consumption during sliding.

Keywords: Abrasive wear; Pearlite steel; Nanoindentation; Vanadium carbide

1. Introduction

Hardness is the mechanical property most used to characterize the wear resistance of materials. Krushchov conducted a large number of the well-controlled wear tests and find the abrasion resistance (the inverse of the abrasive wear rate) of metals to be proportional to the bulk hardness [1,2]. It has been also reported that abrasion-induced subsurface deformation and work hardening along with related microstructural changes are found to be an important factor controlling the material removal mechanisms. Thus, several efforts are underway to investigate abrasive wear resistance by way of bringing about microstructure changes [3–8].

Studies have been made of the relationship between typical microstructures of steels (such as pearlite, martensite, bainite and ferrite) and wear behavior of materials during wear. Abrasion-induced microstructure changes were studied via metallographic examinations of longitudinal sections (parallel to the sliding direction) and the surface hardness using a microhardness tester [9–11]. While these studies provide an insight into hardness as a function of depth from the abraded surface in a micrometer scale, the nanohardness close to the abraded surface is still not clear because the severe plastic deformation and work hardening localized within a small volume of material adjacent to contact surfaces [3].

In the present study, we carried out to study the effects of the abrasion-induced nanohardness changes on the abrasive wear resistance of a pearlite steel [12]. An attempt has also been made to examine the role of the interlamellar spacing and microalloying with vanadium additions in controlling the wear resistance [13]. We use a depth sensing nanoindentation technique, which is a powerful tool for nanomechanical testing at very small scales and very high resolution [14,15]. The wear test is performed by using a pin-on-disc machine to evaluate the abrasion resistance against the abrasive paper. The relationship between the nanohardness of the abraded surface region and the abrasion

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resistance are considered to elucidate the micro mechanism of the sliding wear of the pearlite steel.

2. Experimental

The pearlite steel utilized in this study was prepared by an induction furnace. The chemical composition is given in Table 1. Hot rolled bars of 20 mm diameter, forged above 1100 °C from a 90 mm diameter, were cooled in an ambient air. Subsequently, some of the bars underwent different heat treatment to change its interlamellar spacing. The details of the heat treatment cycles and corresponding interlamellar spacing, the bulk hardness by the conventional Vickers indenter are also shown in Table 1. The volume fraction of a ferrite phase of each specimen was less than 10%. Testing surface (2 mm × 3.7 mm) of the specimen was mirror-polished by emery paper and buffing, then finished by an electrolytic polishing with the Pt cathode in a solution of 5% percholic acid, 95% acetic acid at 8 °C under the potential of 40–50 V to remove the mechanically damaged surface layer.

Two-body abrasive wear test was performed on a small square tip (2 mm × 3.7 mm × 1.3 mm) of the specimen. The tests were conducted using a pin-on-disk machine in an ambient atmosphere. A schematic representation of the test configuration is shown in Fig. 1. The specimen is ground on an abrasive paper at an applied load of 2.1 N, a sliding speed of 0.66 m/s and traversal distance of 1980 m, and when in motion the specimen run on the same track under the air blow to remove debris particles. Crushed silica particles (size: 15–67 μm) were used as the abrasive medium. The specimens were thoroughly cleaned, dried and weighed prior to and after each wear test. The wear rate was calculated from weight loss measurement. Weight data were converted to volume loss using steel density of 7760 kg/m^3.

Nanoindentation tests were performed on surfaces worn under same wear conditions using a commercially available apparatus (Triboscope, Hysitron Inc.). A Berkovich indenter was used for all indentations. The contact area of the indenter tip as a function of contact depth was calibrated by performing a series of indents on a standard fused silica sample [16]. Nanohardness is defined as the load divided by the contact area of the indentation. It is the mean pressure, which a material will support under load. The testing load values were 100, 200, 500, 1000, 2000 μN. The loading rate was constant of 200 μN/s. A commercial type atomic force microscope (AFM) (Nano scope III, Digital Instruments Inc.) with a nanoindentation apparatus was used for both the hardness test and surface observation. Probed sites and indent configuration on the specimen surfaces were

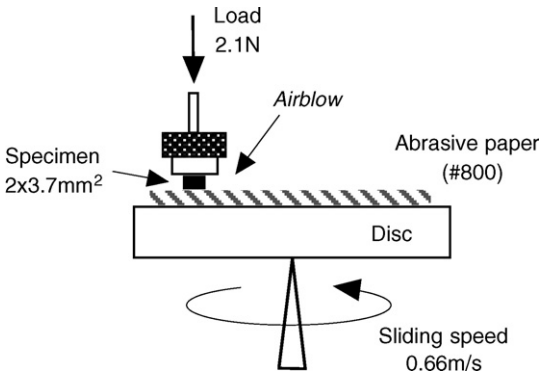

Fig. 1. Schematic illustration of the pin-abrasion apparatus.

confirmed before and after the indentation measurements. In order to obtain reliable results, for each applied load, more than 10 indentations were performed at randomly selected locations on a worn surface.

After abrasion tests, specimens were sectioned perpendicular to the wear surfaces. Longitudinal sections were examined in the scanning electron microscope (SEM) and transmission electron microscope (TEM) to clarify the wear-induced microstructural changes in the regions close to the abraded surface [17]. Thin foil samples for TEM observations of the worn surface were cut parallel to the wear direction and perpendicular to the worn surface by micro cutting, without plating or coating. The samples were then mechanically polished and thinned to a thickness of about 100 μm and further thinned using a focused ion beam technique. We used a FEI model-FIB 2000 with a Ga ion beam at 30 kV.

3. Results

3.1. Abrasion tests

The variations of cumulative wear depth (wear volume/testing surface area) with sliding distance for the plain carbon steel specimens LP1, LP2 and LP3 are shown in Fig. 2. Bulk hardness of these specimens follows Hall–Petch relationship with interlamellar spacing; the hardness is inversely proportional to the square root of interlamellar spacing [4]. It is clearly shown that the wear depth decreases with the bulk hardness. Fig. 3 shows that the cumulative wear depth with sliding distance for 0.26V, 0.05V and V-free steel. The vanadium additions lead to an increase in the bulk hardness due to precipitation hardening of vanadium carbide [13]. It may be noted

Table 1
The chemical compositions (wt.%), HV hardness, lamellar spacings (nm) and heat treatments of specimens

Number	C	Si	Mn	S	Cr	V	Hv	Lamellar spacing	Heat treatment
LP1	0.72	0.07	0.19	<0.001	0.03	<0.01	268	150	As-forge
LP2	0.72	0.07	0.19	<0.001	0.03	<0.01	312	113	950 °C/60 min, −5 °C/s
LP3	0.72	0.07	0.19	<0.001	0.03	<0.01	360	75	950 °C/60 min, −15 °C/s
0.26V	0.38	0.23	1.02	0.17	1.5	0.26	285	122	As-forge
0.05V	0.45	0.27	0.98	0.167	1.48	0.05	273	128	As-forge
V-free	0.4	0.23	0.99	0.17	1.5	<0.01	246	122	As-forge