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Sliding friction induced atom diffusion in the deformation layer of 0.45% C steel rubbed against Tin alloy

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ABSTRACT

Evolution of microstructure and compositions in worn surface and subsurface of 45 (0.45 mass% carbon) steel disc slid against tin-alloy-pin was analyzed by SEM, TEM and SIMS. The mechanical alloying layer and plastic deformation layer were formed in the sliding friction-induced deformation layer (SFIDL) of 45 steel. Ultra-refine and nano grains were detected in the worn surface layer. Elements of Sn, Cu and Sb, originated from the mating tin-alloy-pin, with diffusion depth of 35 μm, 11 μm and 4 μm, respectively, were detected in its SFIDL. Mechanisms accelerating atom diffusion in SFIDL were subsequently propounded.

1. Introduction

The composition, structure, hardness and properties influencing the tribological behaviors of a tribo-surface are usually modified when it is in the process of operation [1]. As a mean of obtaining an excellent tribological surface, many researchers have devoted substantial effort to investigate the evolution of microstructure and composition in sliding friction-induced deformation layer (SFIDL) of metallic materials since 1970s [2–6]. Studies [5–9] have indicated that the action of tribological processes is likely to cause large plastic strains and strain gradients in the surface layer of two interacting materials. Such plastic deformation may subsequently result in drastic change of microstructure in surface layer. Systematic investigation on the evolution of microstructure in the SFIDLs of tribo-couple thus facilitates a better understanding of the friction and wear behaviors of the mating materials.

Available literature [1,3,5,8–10] has reported the formation of ultra-refine or nanocrystalline structure in the SFIDL of metallic materials. Such formation is mainly due to the causation of large shear stress by the sliding friction. In addition, point and line defects in the SFIDL may accelerate the exchange and/or diffusion of atoms between the contact surfaces under frictional condition. Moreover, friction rises temperature to promote atomic diffusion between the frictional surfaces. Typically, D'Acunto [11] has been able to evaluate wear volume at the tip of a sliding asperity using a diffusive model although experimental evidence relevant to this field is still rather lacking. Typical example on atom diffusion behavior during friction process can be seen: (i) by the diffusion of elements into chip of workpiece when high speed cemented cutting tool is worn off [12–20]; and (ii) in hot forging die [21]. The study of Zhang et al. [22] on the atom diffusion behavior between cutting tool and workpiece has found the diffusion of carbon, tungsten, and cobalt atoms in the tip of cemented carbide tool diffused into the chip of workpiece during high-speed cutting. As the result of such diffusion, the hardness and wear resistance of the tip decreases. Generally, the composite gradient and temperature rise due to friction effect, together with defects caused by shear stress, may lead to different chemical compositions in and atom diffusions between the metallic tribo-pair. Study of Lu et al. [23] verified the significant enhancement of nitriding kinetics for the iron treated with nanostructured surface layer. Consequently, investigation on the alloy element diffusions between metallic tribopair in dry sliding friction condition undoubtedly facilitates the understanding of the relationship of wear process and evolution of microstructure in SFIDL.

This paper reports our study on the evolution of microstructures and the phenomena of atom diffusion in the SFIDL of 0.45 mass% carbon steel slid against ZChSnSb11-6 tin alloy under dry frictional condition. It also discusses the possible mechanisms of grain refinement and accelerating atom diffusion. Experiments for this study have been conducted using a disc-on-pin friction test rig

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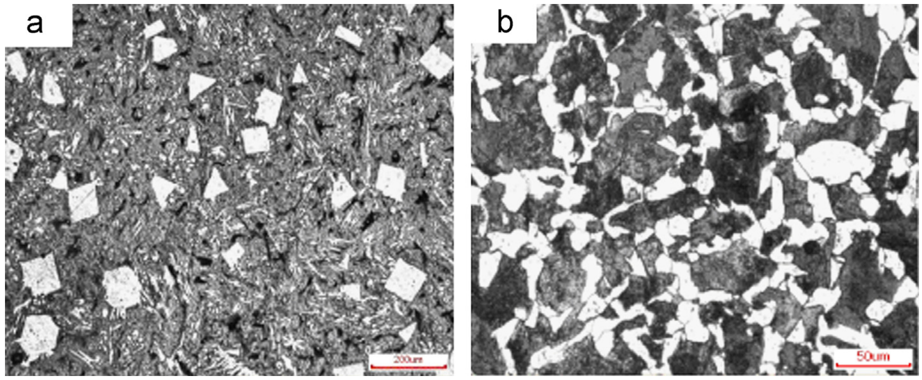

Fig. 1. Optical micrographs of tin alloy (a), and 0.45% C steel (b).

and discussions have been based on the evidences derived from the relevant experiments.

2. Experimental details

2.1. Materials and wear test

The disks were made of normalized 0.45% C steel composed of ferrite and pearlite and the pins were made of commercially cast tin alloy (ZChSnSb11-6) containing 11.5 wt % Sb and 5.5 wt % Cu (Sn in balance). The microstructure of the Tin alloy was as shown in Fig. 1(a) and its counterpart for the 45 steel was illustrated in Fig. 1(b). The pins having 6 mm diameter and 20 mm length and the discs having 70 mm diameter, 5 mm thickness with 8 mm diameter hole in their respective center were firstly prepared by an EDM-wire-cut process. Both pins and disks were then grinded mechanically to surface roughness *Ra* of 0.05–0.1 μm and *Ra* of 0.03–0.09 μm, respectively. Since the investigation was initially aimed at simulating the wear behavior of axial against bearing bush in their extreme condition, the pin-on-disc tests were thus undertaken under the dry sliding frictional condition.

The dry sliding frictional tests were carried out using a Germany made SST-ST disc-on-pin wear test rig. The tests were performed with the center of the stationary pin specimen fixed 24 mm away from the center of the rotary disc specimen, and under loading of 50 N with relatively rotational speed of 400 rpm.

2.2. Observation of worn surface and friction induced surface layer

A metallographic specimen was EDM-wire-cut along the sliding direction of a slid SFIDL of the disc, which was then cool-inlayed with tooth acrylic resin. It was then grinded and polished with SiC sand paper, and etched with a 4% nitric acid alcohol solution. It was then followed by removing the tooth acrylic resin and ultrasonically cleaned using acetone solution. The slid SFIDL of the so-prepared disc specimen and its surface compositions were subsequently analyzed using a HITACHI S-570 scanning electron microscope with a 20 kV energy spectrum (SEM and EDS).

To analyze whether there was any possible grain refinement on the utmost top of the slid surface, individual 0.5 mm thick slices were wire-cut along the depth direction of the slid disc, which were carefully thinned to a thickness in range of 30 μm–50 μm by gradually grinding off the slices from their non-slid surface. Transparent tape was used to protect the worn surface of the thinned specimens which were then punch-pressed into 3 mm diameter wafers. After single-jet electropolishing and ion thinning for 30 min, the worn surface was analyzed using JEM-2010 high resolution transmission electron microscopy (HRTEM).

2.3. Atom diffusion analysis

A Cameca IMS 6F secondary ion mass spectrometry (SIMS) was employed to detect any possible phenomenon of atom diffusion between the SFIDL of 0.45%C steel disc and tin alloy. As SIMS is a most powerful and versatile surface analytical tool for studying the chemical and distributional information of a wide range of species [24,25], it was used to acquire both types of information in our study. These types of information were collected from slice of 8 mm × 8 mm × 1 mm wire-cut along the depth direction from the relevant slid specimen. The wire-cut slice was firstly ultrasonically cleaned using acetone solution and its slid surface was then bombarded with oxygen ion beam in a vacuum condition. The spot diameter of the bombarding oxygen beam ranged between 1 μm and 2 μm, and was controlled to impact upon the middle of the slid track. Under the bombardment, the surface of slice was stripped off layer by layer and atoms in each layer were collected by its secondary ion signal in the center of sputtering pit. A mass spectrometer was then used to monitor synchronously the six chemical elements of Fe, C, O, Sn, Cu, and Sb. Their corresponding secondary ion intensity was also collected; the obtained curve of secondary ionic strength for each layer across the depth of the specimen slice was hence used for the analysis of the possible atom diffusion behavior in the SFIDL.

3. Results and discussion

3.1. Friction-induced deformation layer

SEM image of SFIDL of the 0.45%C steel disc was shown in Fig. 2(a) and the chemical composition scanned by EDS across the dot B was shown in Fig. 2(b). The plastic flow lines appearing in the matrix as shown in the SEM clearly illustrated a tendency to incline to the utmost slid surface (Fig. 2(a)), with results almost similar to those reported in Ref. [26,27]. It appeared that closer to the slid surface resulted in severer deformation. Moreover, white bright layer was also observed beneath slid surface. EDS analysis (Fig. 2(b)) suggested the main elements in white bright layer were almost the same as those in pin. Additionally, there were also oxygen, iron and carbon to be detected from both atmosphere and tribo-couple.

The SEM (Fig. 2(a)) divided the SFIDL into two layers, namely [26]: (i) mechanical alloying layer (MML); and (ii) serious plastic deformation layer. The bright white layer in MML was about 1 μm–2 μm thick and appeared similar to the so-called “white layer” which has only been seen in the high carbon steel [28,29]. Usually, the amount of heat inevitably produced in the process of dry sliding friction [30,31] greatly influences the evolution of microstructure in the slid surface. The lower strength and melting point