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Tribology International 39 (2006) 417–425

TRIBOLOGY INTERNATIONAL

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Wear particles, surfaces and plastic flow generation in unimplanted and Mo ion implanted carbon steel under friction

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Available online 14 June 2005

Abstract

The purpose of the present work is to study the influence of the structure modified by ion implantation on mechanisms for wear particles, surfaces and plastic flow generation. The 'block-on-shaft' testing procedure was used to investigate the wear behavior of the ferritic/pearlitic carbon steel (in 0.45 wt% C) in the unimplanted and Mo ion implanted states. New approach to description of plastic deformation and destruction under friction is introduced on the basis of concepts of structural levels of plastic deformation and physical mesomechanics. In order to investigate the plastic flow behavior under friction, a unique method was applied using the optical TV-complex 'TOMSC'. Reconstruction step-by-step of the displacement vector fields helps to reveal different plastic deformation stages evolving from fragmented mesostructure to large vortex mesostructure. It has been found that the character of plastic flow in the subsurface layers during friction determines the mechanism for generation and separation of the wear particles and formation of the wear surfaces. It was concluded that the formation of the modified structural-phase state in the surface layer of the Mo ion implanted specimens prevents the fragmented structure formation at mesolevel and retards the mesofragment vortex movement in the subsurface layer, thereby decreasing the intensity of the wear particles generation and finally increasing wear resistance.

Keywords: Wear particles; Plastic flow; Microstructure; Deformation scale levels; Ion implantation

1. Introduction

One of the most important problems of the friction physics is plastic flow, surface topography and wear particles in tribocontacts of sliding parts. The analysis of wear particles and surface topography can be used to identify the wear mechanisms in the surface layers during friction [1–3]. There are a lot of experimental data illustrating wear mechanisms changes and wear resistance improvement due to some surface modification methods, such as particle beams and plasma flow treatments [4–8]. It is well known, that high dose ion implantation gives rise to a considerable modification of the microstructure, thereby decreasing wear of the near-surface layers [6–10]. However, there are no clear concepts, which can explain the changes of the wear mechanisms after ion implantation.

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doi:10.1016/j.triboint.2005.04.022

The purpose of the present work is to study the influence of the structure modified by ion implantation on mechanisms of wear particles, surfaces and plastic flow generation. A new approach to the description of plastic deformation and destruction under friction is introduced on the basis of concepts of structural levels of plastic deformation and physical mesomechanics.

Physical mesomechanics describes a loaded solid as a hierarchic system in which the deformation and destruction processes at micro-, *meso*- and macroscale levels are self-consistent [11–13]. Plastic deformation of a loaded solid at the microlevel is realized by the generation and motion of dislocations forming the dislocation substructures [14,15]. Transmission electron microscopy is one of the principle methods of investigation of plastic deformation at the microlevel. During deformation the dislocation density increases and when a particular critical density is reached, the local structural transformations takes place over a large distance forming the fragmented structure [16]. A new type of three dimensional volume carrier of plastic deformation appears at this scale level. Plastic flow at this scale occurs following the 'shear and rotation' scheme and is classified as the mesolevel in [11]. To make the direct visualization of plastic flow development at the mesolevel possible the ‘TOMSC’ optical TV-complex has been developed in the Institute of Strength Physics and Materials Science of SB RAS [17]. At the same time, Scanning electron microscopy and optical microscopy can be used effectively to study deformation at the mesolevel. Fracture is the final stage of the fragmentation when its scale changes from the *meso*- to the macrolevel. The analysis of the stress–strain curves and wear curves allows to obtain information about plastic flow of a specimen as a unit, that is at the macrolevel.

2. Experimental procedure

The material used for this study was medium carbon steel (0.45 wt% C), with ferritic and pearlitic components and an average grain size of 20 μm.

The ‘Diana-2’ vacuum-arc metal ion source [7] was used for the ion implantation. The Mo ions were implanted at an accelerating voltage of 60 kV to a dose of 1×10^{17} ion/cm^2.

The ‘block-on-shaft’ testing procedure was used to investigate the wear behavior of the unimplanted and Mo ion implanted steel. The sliding conterface was chromium bearing steel (1.5 wt% Cr). Tribotechnical tests were carried out at a sliding speed of 1 m/s and a 150 N normal load in the lubricated environment. The magnitude of wear was calculated with the relation:

$$h = \frac{\Delta M}{\rho \times S},$$

where h is the wear depth, ΔM is the mass change of specimens during testing, ρ is material density, S is the contact area under friction.

In order to investigate the plastic flow behavior under friction, the unique method [18,19] was applied using the optical TV-complex ‘TOMSC’. The operational principle of the optical TV-complex ‘TOMSC’ is based on computer processing of a series of the deformation relief optical images. Some specific topology is formed as the result of deformation development at the longitudinal cross-section of the specimen under load. Precise positioning of the images of surface regions of the specimens was done in relation to the two coordinates using the special software [17] for image processing. It allows to construct the displacement vector fields and to examine the plastic flow character at the mesolevel.

Auger electron spectroscopy (AES) was used to determine the Fe, C, O and Mo depth concentration. The microstructure was investigated using Transmission electron microscopy (TEM). Scanning electron microscopy (SEM) was used to investigate the morphologies of wear surface and wear particles.

3. Experimental results and discussion

3.1. Wear curves, wear particles and surfaces

A considerable improvement of wear resistance of ferritic/pearlitic steel after Mo ion implantation treatment is observed. The typical dependence of the wear depth on sliding time for the friction couple ‘carbon steel–chromium steel’ both before and after Mo ion implantation is presented in Fig. 1. It can be seen that, first, the wear rate of unimplanted specimen monotonically increases during first 20 min, then it becomes almost constant and a transition from the run-in stage to the steady-state wear stage is observed. The running-in wear for the ion implanted specimen is much less and the steady-state wear is reached more rapidly. Many researchers [4–6,20,21] also observed such improvement of wear resistance after ion implantation. However, so far no adequate concepts which can explain the causes of improvement of the wear resistance after ion implantation.

Fig. 2 illustrates a typical wear surface and particles, produced during the run-in period of unimplanted steel. Different grooves can be seen in the SEM micrographs of unimplanted wear tracks. Three typical sizes of the groove corresponding to the three scale levels can be distinguished: 1—units of micrometers, 2—tens of micrometers, 3—hundreds of micrometers. The geometrical parameters of wear particles have also three typical sizes.

A typical wear surface and particles, produced during wear testing of Mo ion implanted steel is presented in (Fig. 3). It can be seen that the wear surface of implanted wear tracks consists of the grooves of the first level (units of micrometers) and single grooves of the second level (tens of micrometers). The cross-section sizes of wear particles

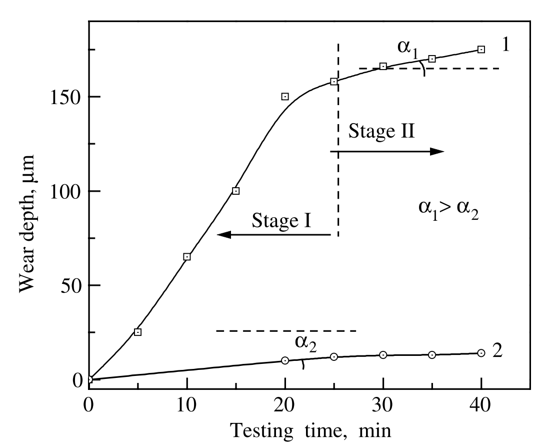

Fig. 1. Dependence of the wear depth on sliding time for the friction couple ‘carbon steel–chromium steel’ under the ‘block-on-shaft’ wear test: (1) unimplanted state, (2) implanted state.