Regularities of Micro- and Mesostructure Formation During Friction and Wear of Ion-Implanted Steel

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Abstracts – The paper presents the results of a comparative investigation of friction and wear behavior of the ferritic/pearlitic carbon steel (in wt.% 0.45 C) and martencitic alloyed steel (in wt.% 0.95 Cr, 0.4 C) in the initial and 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. It was concluded that the formation of the modified structural-phase state in the surface layer of the ion implanted steels prevents the fragmented structure formation at mesolevel and retards the mesofragment vortex movement in the subsurface layer, thereby decreasing the intensity of the wear particle formation and increasing wear resistance.

1. Introduction

There are a lot of experimental data illustrating wear mechanisms changes and wear resistance improvement due to some modification surface methods, such as particle beams and plasma flow treatments [1]. It is well known, that ion implantation gives rise to a considerable modification of the microstructure, thereby decreasing wear of the near-surface layers. However, there are no clear concepts, which can explain the changes of the wear mechanisms after ion implantation.

The paper presents the results of a comparative investigation of 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 [2]. Plastic deformation of a loaded solid at the microlevel is realized by the generation and motion of dislocations forming the dislocation substructures. TEM 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 take place over a large distance forming the fragmented structure. Plastic flow at this scale occurs following the "shear and rotation" scheme and is classified as the mesolevel. To make the direct visualization of plastic flow development at the mesolevel possible the "TOMSC" optical TV-complex has been developed in the ISPMS of SB RAS. At the same time, SEM 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.

The above-mentioned approach was applied for the comparative investigation of friction and wear behavior of unimplanted and implanted steels.

2. Experimental Procedure

The materials used for this study were ferritic/pearlitic carbon steel (in wt.% 0.45 C) and martencitic alloyed steel (in wt.% 0.95 Cr, 0.4 C).

The "Diana-2" vacuum-arc metal ion source [3] was used for the ion implantation of ferritic/pearlitic carbon steel. The Mo ions were implanted at an accelerating voltage of 60 kV to a dose of $1 \cdot 10^{17}$ ion/cm^2. Modification of surface layers of martencitic alloyed steel was carried out with the low-energy high-current ion-beam method [4]. The N ions were implanted at an ion energy of 3 keV and temperatures of 670 K and 770 K to a dose of $3 \cdot 10^{19}$ ion/cm^2. It allows to vary thickness of surface modified layers.

The "block-on-shaft" testing procedure was used to investigate the wear behavior of the unimplanted and ion implanted steel. The sliding conterface was the 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.

In order to investigate the plastic flow behavior under friction, the original method [5] was applied using the optical TV-complex "TOMSC" [2]. AES was used to determine the depth concentration. SEM was used to investigate the morphologies of wear surface and wear particles. The structural-phased state and the microstructure were investigated by XRD and TEM.

3. Experimental Results

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 [1] 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.

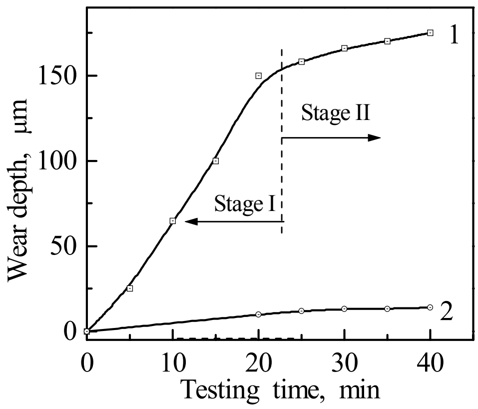

Fig.1. Dependence of the wear depth on sliding time for the friction couple "carbon steel-chromium steel" under the "block-on-shaft" wear test: 1) unimplanted state, 2) Mo ion implanted state

To explain these processes it is necessary to study and compare the plastic flow development in near-subsurface layers, their fracture under friction both before and after ion implantation within the framework of the multiscale level approach.

The level-by level TEM studies have shown that the gradient fragmented microstructure is formed in near-surface layer of the unimplanted carbon steel under friction (Fig. 2). This microstructure is characterized by decreasing of plastic deformation at some distance from surface. The succession of layers with different structure can be distinguished. A very thin quazi-amorphous layer is formed on friction surface (Fig. 2, a). Two diffuse aureoles can be seen in a microdiffraction pattern (inset in Fig. 2, a). In this layer the composition of the material is changed. The detected O and C point to intermixing processes in this layer. The modified zone is spread over than 300 nm. The next layer is located beyond quazi-amorphous one (Fig. 2, b). The microdiffraction pattern (inset in Fig. 2, b) has the form of quasi-rings, which indicate the sub-microcrystalline structure. The microdiffraction analysis of this layer has shown the phase composition for initial state of the carbon steel (α-Fe and Fe_3C). The average grain size in this layer is 0.05 μm. The fragmented layer is formed beyond it (Fig. 2, c). In this layer the individual grains are divided into the fragments with high dislocations density.

In short, the fragmentation process at the microlevel takes place as a result of the plastic deformation of the near-surface layers of the unimplanted steel at the run-in period.

However, the fragmentation process turned out to occur not only at the microlevel, but also at the mesolevel. The optical TV-complex "TOMSC" allowed some new features of the plastic deformation to be revealed at the mesolevel under friction. Fig. 3 shows the optical images of the deformation microrelief formed in the cross-section of the unimplanted carbon steel specimen after friction during 15 min (a) and 20 min (b), the corresponding field of displacement vectors (c). The displacement vectors, which characterize the intensity of plastic deformation, are oriented in direction of applied load. The length of vectors is maximum near to the surface and it is decreased at some distance from the surface of the specimen, this indicates the gradient mesostructure formation in the subsurface layer. The analysis of the displacement vector field allows to distinguish some features of the deformation relief. It can be seen that the fragmented mesostructure with the mesofragment

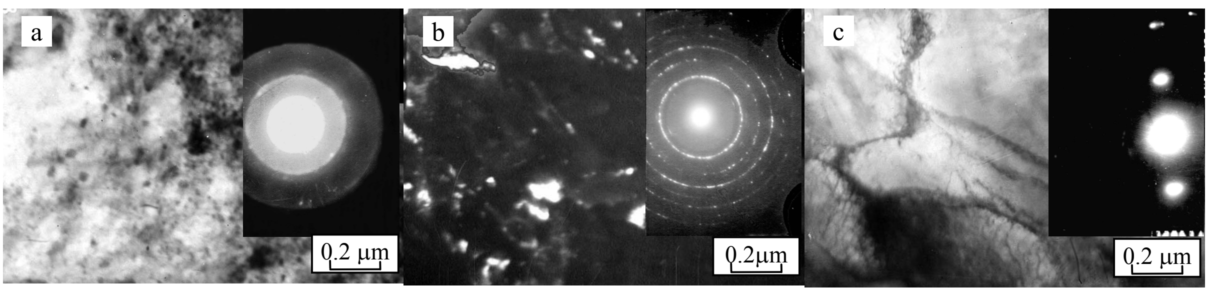

Fig. 2. TEM bright (a, c) and dark field images (b) and the corresponding SAD of surface layer of the unimplanted carbon steel under friction: a) quazi-amorphous structure; b) sub-microcrystalline structure; c) fragmented structure

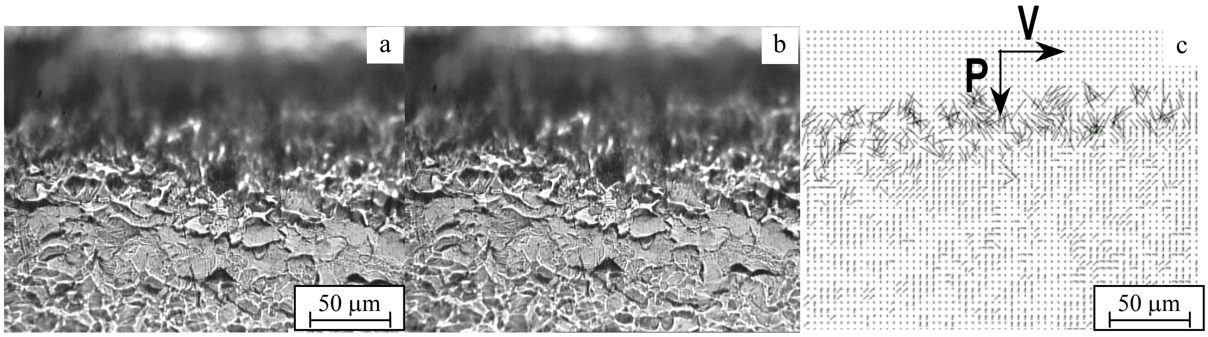

Fig. 3. Optical images of the deformation microrelief formed in the cross-section of the unimplanted carbon steel after friction during 15 min (a) and 20 min (b), the corresponding field of displacement vectors (c): P is the applied force direction, V is the rotation direction of the friction machine ring

sizes 25–50 μm is formed in the subsurface layer. The direction of displacement vectors is identical inside every mesofragment, while the orientation of the displacement vectors varies from one mesofragment to another.

The results presented demonstrate that fragmentation process at the micro- and mesolevels takes place during friction of unimplanted steel. The adaptation of material to friction process at the run-in period is accompanied by gradient micro- and mesostructure formation.

It is turned out that the similar microstructure is formed in near-surface layer of carbon steel after Mo ion implantation (Fig. 4). The level-by-level TEM studies allows to distinguish the quaziamorphous and fine dispersed structure in the Mo ion implanted layer. AES analysis has shown that the profile of Mo introduced by ion implantation has maximum located at a distance from surface. In the ion-implanted layer not only Mo, but also impurities of O and C are detected. It should be pointed that the impurities of O and C are intermixed during ion implantation, thereby also modifying surface layer. The modified zone exhibits an extension of more than 50 nm. The microdiffraction analysis of this layer showed that secondary phase is formed. It is Fe_2Mo_4C phase. On the microdiffraction pattern (inset in Fig. 4b) not only the rings of the ion implanted layer but also matrix reflexes can be seen since the implanted layer is much thinner than the TEM thin foil. The next layer is subsurface layer with the high density dislocation structure induced by ion implantation (Fig. 4c). The dislocation structure is heterogeneous. It varies from cell-net substructure up to fragmented structure. The thickness of the ion-affected layer varies from ten micrometers up to hundred micrometers.

Thus, the gradient microstructure modified by alloyed elements is formed in near-surface layer after ion implantation. In many respects this microstructure is similar to structures formed in the near-surface layers during friction at the run-in period (Fig. 2).

The comparative analyses of plastic flow development in the unimplanted and ion implanted steels allow to reveal some features of the fracture of near-surface layer under friction illustrated in this scheme (Fig. 5). We have mentioned above that until the wear-protective layers fragmented at the micro- and mesolevel are not formed the run-in period is not completed. These layers retard the generation of wear particles at the steady-state wear stage, thereby decreasing wear rate. Despite the fact that the considerable reduction of wear at the steady-state wear stage takes place, the plastic flow occurs in subsurface layers. The step-by-step construction of the displacement vector fields helps to reveal different plastic deformation stages. We have mentioned above that the fragmented mesostructure with mesofragment sizes 25–50 μm is observed in displacement vector fields (Fig. 3). As the sliding time increases, the mesofragment sizes grow up to 100 μm and then the large

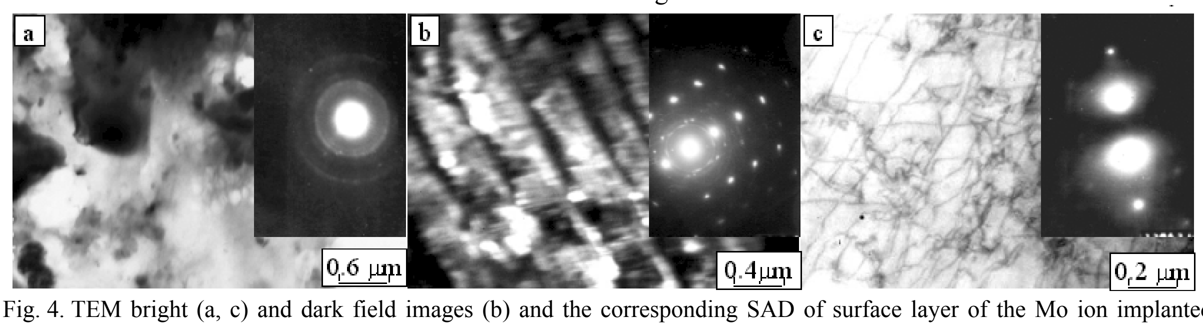

Fig. 4. TEM bright (a, c) and dark field images (b) and the corresponding SAD of surface layer of the Mo ion implanted carbon steel: a) quazi-amorphous structure; b) fine dispersed structure; c) high dislocation density structure

vortex mesostructure is observed in displacement vector fields. When a particular critical deformation is reached the fracture of subsurface layer happens, thereby generating wear particles. At the same time the single large-scale elongated particles are formed. The cross-section sizes of these particles are 300–400 μm and it corresponds to the fragment sizes of the vortex mesostructure identified in the displacement vector fields. It determines the mechanism for generation and separation of large wear particles and fracture of near-surface layer of unimplanted steel.

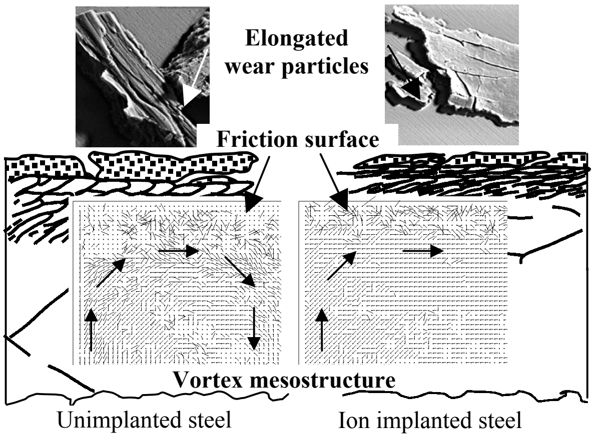

Fig. 5. The scheme of plastic flow development in the unimplanted and ion implanted steel and fracture of near-surface layer under friction

The gradient microstructure, modified by Mo ion implantation, results in a localization of the plastic deformation in the thin subsurface layer during the very first moments of wear testing. In its turn it impedes the development of vortex mesostructure in the subsurface layers under friction. As a result, decreasing of the intensity of the wear particle formation takes place, thereby improving wear resistance.

Low-energy N ion implantation at 670 K of alloyed steel results in the formation of modified subsurface layer of thickness of which is equal to 40–60 μm. Microhardness of this layer is 1100 MPa. Analysis of X-ray data revealed matrix α-Fe, high-nitrogen hexagonal ε-Fe_3N and low-nitrogen γ′-Fe_4N.

N ion implantation at 770 K increases of thickness of modified layer up to 70–80 μm decreases of microhardness up to 9500 MPa. The basic phase of hardened layer is γ′-Fe_4N.

The formation of high-strength surbsurface layers at low-energy N ion implantation leads to a localization of the plastic deformation in the thin subsurface layer during the very first moments of wear testing as in the case of high dose ion implantation and also prevents the fragmented structure formation at mesolevel. It also retards the mesofragment vortex movement in subsurface layer and improves tribological behavior for both temperature regimes. However, most high level of wear resistance is observed for alloyed steel implanted with N ions at 670 K (Fig. 6). It occurs due to precipitation of high concentration ε-Fe_3N at 670 K. The precipitation of low concentration γ′-Fe_4N at 770 K causes to reducing wear resistance.

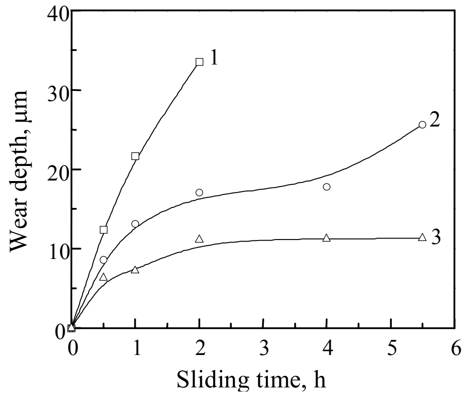

Fig. 6. Dependence of the wear depth on sliding time for the friction couple "alloyed stee–chromium steel" under the "block-on-shaft" wear test: 1) unimplanted state, 2) N ion implanted state, 770 K, 3) N ion implanted state, 670 K

4. Conclusion

The set of the above described results allows to state the following conclusions:

1. The fragmentation process at the micro- and mesoscale levels takes place as a result of the plastic deformation of the material near surface layers during run-in period.
2. The vortex character of plastic flow in the subsurface layers during friction determines the mechanism of generation and separation of the large wear particles and fracture of near-surface layer.
3. The generation of the modified structural-phase state in the surface layer occurs due to ion implantation. In many respects this gradient microstructure is similar to the structure formed in the near-surface layer at run-in stage.
4. The gradient microstructure formed after ion implantation result in a localization of plastic flow in thin subsurface layer and retards the vortex mesostucture initiation, thereby decreasing the intensity of the wear particle generation and finally increasing wear resistance.

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