Surface layer structure of AISI 1020 steel at different stages of dry sliding under electric current of high density

K A Aleutdinov[1,*] , V Ye Rubtsov[1,2,], V V Fadin[2] and M I Aleutdinova[2,3]

[1] National Research Tomsk Polytechnic University, Institute of Cybernetics, Lenin avenue, 30, Tomsk, 634050, Russia
[2] Institute of Strength Physics and Materials Science, pr.Akademicheskii, 2/4, Tomsk, 634021, Russia
[3] Seversk Technological Institute - branch of State Autonomous Educational Institution of Higher Professional Education «National Research Nuclear University «MEPhI», pr.Kommunisticheskii, 65, Seversk, 636036, Russia

*E-mail: aleut@ispms.ru

Abstract. Wear intensity of the sliding electric contact steel 1020/steel 1045 depending on sliding time is presented at the contact current density higher than 100 A/cm^2 without lubricant. It is shown that wear intensity of 1020 steel decreases at increasing of sliding time. Wear intensity is stabilized after some sliding time. This time (burn-in time) decreases at reduction of current density. Structural changes are realized in surface layer. Signs of liquid phase are observed on sliding surface. This liquid isn't a result of melting. It is established using Auger spectrometry that the contact layer contains up to 50 at.% of oxygen.

Keywords: structure changes of surface layer, contact spots, sliding current collection, wear intensity, chemical composition of sliding surface.

1. Introduction

It is known that high wear resistance of material during friction is reached due to structural stability of its contact layer [1]. The structure of surface layer (SL) can be stabilized by superficial hardening, for example, owing to chemical heat treatment, ionic implantation, etc. The structural state of sliding surface will be stable also in the case when external influence doesn't lead to its plastic deformation. It means that the contacting microvolumes will be deformed in the mode of elastic deformation or, more precisely, in the mode of high-cycle fatigue. Therefore creation of the strengthened SL and concrete microgeometry of a surface are expedient only for the friction modes, which don't break surface layer stability.

The heavy mode of friction causes plastic deformation of SL and its subsequent deterioration occurs in the conditions of low-cycle fatigue [2,3]. Surface material self-organizes in this case and its structural changes take place. Thus it is formed the layer of friction induced structures (FIS) as it is shown in [4]. This layer has parameters of structure (thickness, roughness, phase and chemical composition, etc.) changing its values according to changes of parameters of external influence on the tribosystem. Structure parameters achieve its equilibrium values during some time at every regime of normal (non

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catastrophic) wear. The same time it is necessary for achievement of stable values of main outputting characteristics of tribosystem (wear intensity, friction coefficient, average contact temperature, etc).
The main mechanism of surface layer material deterioration is connected with its plastic deformation and its fragmentation [2,3,5]. Suppression of fragmentation and a transfer of SL plastic deformation on lower structural level can be carry out in material capable to well stresses relaxation in the vicinity of stress concentrators. The relaxation of stresses should occur due to local plastic shears. Such local shear instability at the meso-scale structural level has to provide the maximum shear stability at the macro-scale structural level, i.e. on the scale of FIS layer. Such structural state of a FIS layer will provide stable and minimal wear intensity.
Change of initial structure parameters is one of the main ways of management of these contact characteristics. Initial material structure is characterized by chemical (element) and phase composition, as well by stress state and plasticity, and by ability to form FIS layer, etc.
The heavy mode of friction can be set by means of electric current of high contact density. As a rule, current collection materials have the graphite containing composite structure where iron or copper [1] serves as a basis. Most of these composites show wear intensity higher, than cast AISI 1020 steel or copper under heavy conditions of dry friction with contact current density higher 100 A/cm^2 [6]. It means that composites form a low-plastic FIS layer which relax stresses more weakly, than a FIS layer of cast copper or steel 1020. Steels hardening by inducing of alloys elements or by solid phases form FIS layers with low plasticity. It leads to realization of high wear intensity in conditions of FIS layer plastic deformation under influence of electric current during dry sliding [6]. Hardening of material by deformation defects, i.e. peen creation, is a known way of initial structure hardening. This method is applied for SL hardening due to sliding of material during some time until burn-in state achieved and wear intensity will not depend on time at set input parameters of a tribosystem. It is of scientific interest to get some idea about efficiency of surface peen creation of material thanks to burn-in during dry sliding in electric contact with the high contact current density. Determination of FIS layer chemical composition and wear intensity in different points of sliding distance should be necessary stages of research in this direction. Carbon steel 1020 may serve as a model material.
The aim of present work is the study of interconnection of wear intensity and surface layer structure changes of carbon steel AISI 1020 under dry sliding and electric current of contact density higher 100 A/cm^2 in different sliding time moments.

2. Experimental details

The peen steel 1020 of hardness *HB*=2740 MPa served as a model specimen. Metallography studying is carried out applying optical microscope Neophot-21. The average chemical composition of surface layer is defined on Auger spectrometer "Shkhuna-2". Wear intensity is determined under dry sliding electric contact at alternating current (50 Hz), contact pressure p=0.13 MPa, sliding velocity v=5 m/s using tribometer SMT-1 by the scheme "pin-on-ring" (figure 1). Quenched AISI 1045 steel (50 HRC) served as a counterbody. Linear wear intensity is determined as $I_h=h/L$, where h is the specimen height change at sliding distance L=9 km. The contact current density is determined as $j=i/A_a$, where i is the current passing through the nominal contact area A_a (A_a=10 mm^2).

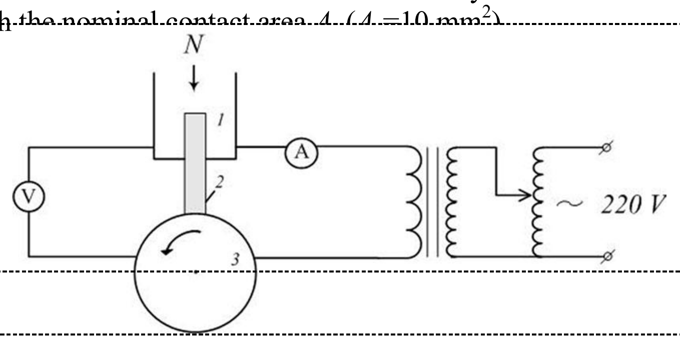

Figure 1. Schematic representation of pin-on-ring test machine structure: 1 - specimen holder, 2 – specimen, 3 - counterbody (steel 1045 HRC).

3. Results

Definition of sliding time sufficient for achievement of stable wear intensity at some set normal wear mode has to be the initial stage of peen studying without reaching of catastrophic wear regime. Normal dry wear of steels under electric current is realized usually till j=400 A/cm^2 [6]. The quasiequilibrium SL structural state of surface layer has to be achieved for shorter sliding time at low current density in comparison with a case of sliding at high current density. It becomes clearly from that the speed (curve slope) of specimen height change during sliding with j=270 A/cm^2 is less than that during sliding with j=400 A/cm^2 (figure 2, a). In other words the stable I_h at j=270 A/cm^2 has lower value than I_h at j=400 A/cm^2 (figure 2, b). It should be noted also that the SL structure can't be equilibrium at the surface peen beginning. It leads to the high height change speed of a specimen (figure 2, a) and to high wear intensity at low sliding time (figure 2, b).

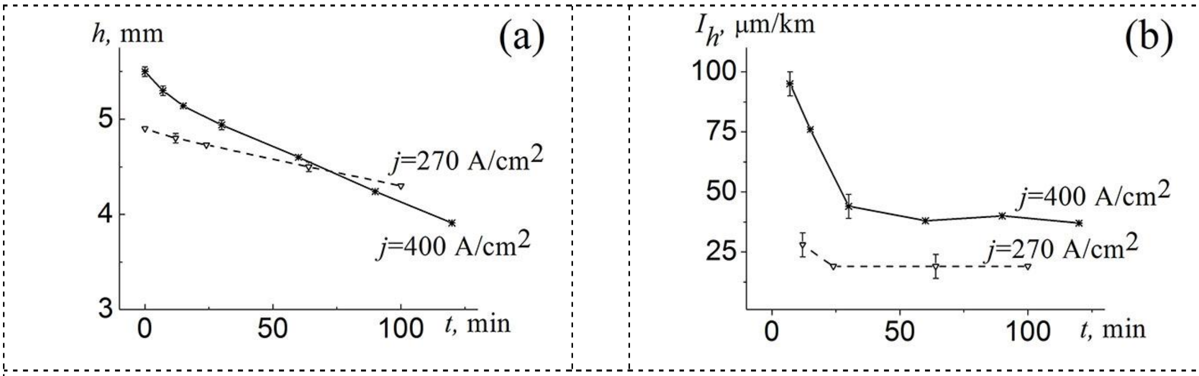

Figure 2. Linear wear (a) and linear wear intensity (b) as a function of the sliding time.

Surface layer structural changes are obvious as a formation of friction induced structure (FIS) layer (figure 3, a-b). One can see that thickness of this layer becomes higher 20 microns in the first 7 minutes of sliding and at sliding time increasing its thickness doesn't change considerably. The same layer appears also during sliding with lower current density.

Signs of liquid phase existence and traces of a surface layer plastic plowing by micro-asperity of counterbody are observed on sliding surface at j>100 A/cm^2 (figure 3, c). Traces of adhesive interaction aren't observed in an explicit form.

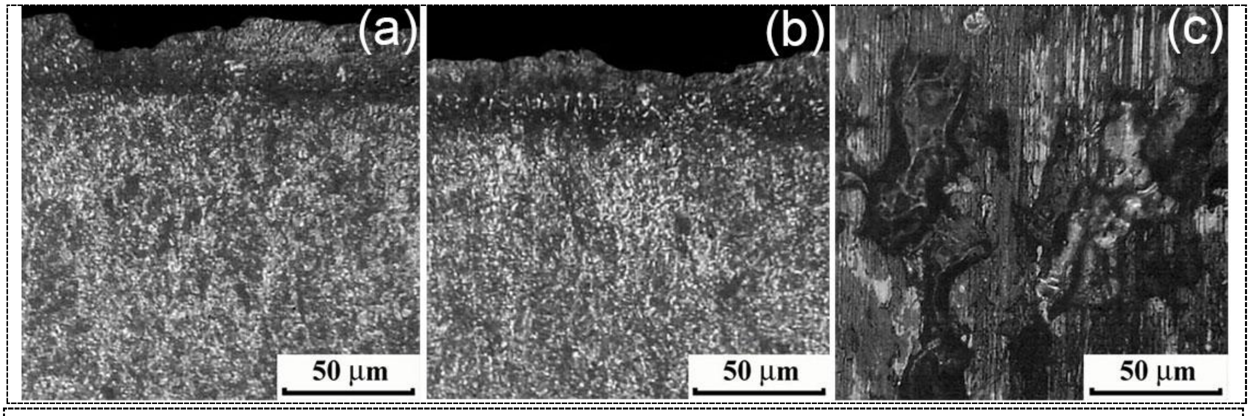

Figure 3. Cross-section of worn surface (a) after sliding at j=400 A/cm^2 for 7 minutes (a) and 120 minutes (b); the OM image of worn surface (c) after sliding at j=270 A/cm^2 for 24 minutes.

Oxygen concentration on sliding surface of steel 1020 reaches values 40-50 ат % (figure 4). It is visible that at initial sliding stage the oxygen concentration can be higher or lower iron concentration (figure 4, a-b). The equilibrium chemical composition of friction induced structures layer corresponds to the equal content of oxygen and iron (figure 4, c). Iron concentration at lower *j*=270 A/cm^2 exceeds oxygen concentration of (figure 4, d).

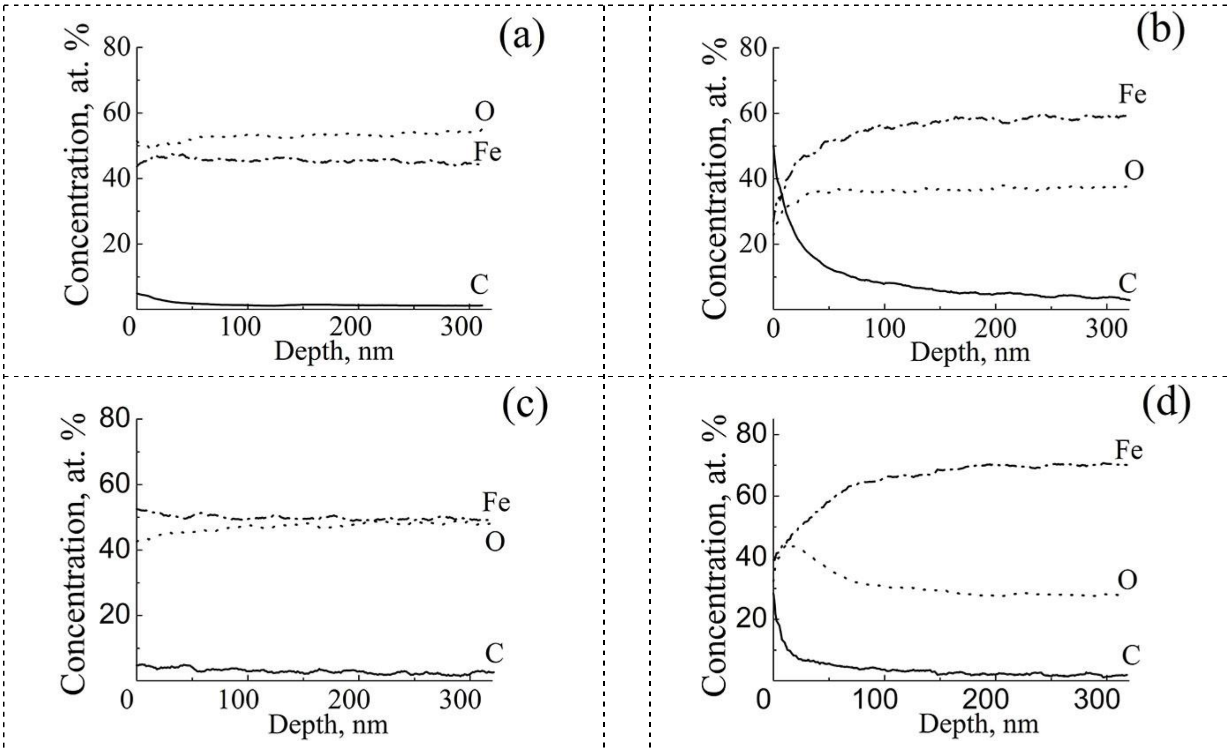

Figure 4. Distribution of chemical elements in contact layer of steel 1020 after sliding at contact current density j=400 A/cm^2 for 7 minutes (a), for 15 minutes (b), for 120 minutes (c) and after sliding at contact current density j=270 A/cm^2 for 24 minutes (d).

4. Discussion

Wear intensity reduction during burn-in process is caused by increasing of surface layer hardness. Deterioration of surface layer begins at exhaustion of FIS plasticity [3,5]. It means that there has to be an optimum ratio of FIS hardness and its plasticity reserve for achievement of the minimum wear intensity. This ratio can be reached for some sliding time. In the general case burn-in time depends on properties of initial structure, on the contact current density and on other input parameters of a tribosystem. Necessary hardness of FIS layer is provided, partly, with presence of the phase FeO, when about 40 at.% of oxygen are placed close to sliding surface (figure 4). If all these oxygen atoms form FeO oxide, so it means that more than a half of thin surface layer is occupied with FeO oxide. Low atomic oxygen concentration in some cases (figure 4, b and figure 4, d) in comparison with higher concentration of oxygen (figure 4, a and figure 4, *c*) in thin surface layer doesn't point to the low volume content of FeO oxide in FIS layer. In this case the absence of regularity in oxygen distribution on sliding surfaces is a consequence of formation of the contact surface sectors having

sharply various structural states. Such distinction of chemical element composition in different places of sliding surface is a usual occurrence independent of initial structure of friction pair materials.
Main ways of external energy dissipation in contact realize as creation of structural defects in surface layer (i.e. FIS layer formation and creation of wear particles) and as thermal streams forming. If high concentration of structural defects is shown in the form of cracks [7] or as severe adhesion of worn surface [8], these are the signs of catastrophic wear. In this case wear particles have the big sizes or big sectors of a plastic flow are observed on sliding surface. But signs of viscous liquid emergence (figure 3, c) shouldn't be considered as a result of catastrophic wear realization. In this case it is necessary to take into account that FIS layer contains a large amount of vacancies. These vacancies provide anomalously high diffusion, first of all, in micro-volumes of contact spots vicinity. As a result it is formed the thin contact layer of high-excited atoms [9] where diffusion can reach the level of the diffusion corresponding to melt of material. But this layer is in a crystalline state. In this case the stress relaxation on these surface sectors can be carried out in accordance with mechanism of viscous liquid deformation [5] when deformation defects are not formed. I.e. signs of viscous liquid existence aren't caused by high temperature in contact. This layer of the strong excited atoms may contain to 50% of oxygen (figure 4), but this oxygen can't be completely connected in FeO oxide since contact electric conductivity in this case has to be low because of high specific resistance of FeO oxide.
Absence of obvious interrelation between wear intensity reduction (figure 2), chemical element composition (figure 4) and optical micro-structure images (figure 3) means that surface layer hardening (i.e. a FIS layer hardening) for some time happens thanks to other mechanism, namely, owing to realization of local plastic micro-shears and formation of deformation defects. Accumulation of defect amount to some limit concentration cause the stress relaxation by formation of cracks and wear particles. It means that the leading mechanism of surface layer deterioration and wear is based on low-cyclic fatigue.

5. Conclusion

Dry sliding of steel 1020 against steel 1045 under the influence of electric current with a contact density higher 200 A/cm^2 leads to changes of surface layer structure. It causes the formation of a friction induced structures layer higher 20 microns thick. This layer contains to 50 at.% of oxygen in the vicinity of sliding surface that points to formation of FeO oxide. Obvious dependence of the oxygen content and FIS layer thickness on the contact current density and on sliding time isn't observed.
Wear intensity decreases during burn-in time to some limit that is conditioned on appearance of deformation defects and contact surface hardening. This wear intensity limit and burn-in time decrease at reduction of contact current density. The stress relaxation in surface layer occurs due to local plastic micro-shears. At the same time other types of a stress relaxation are realized, namely local liquid phase formation and emergence of the high-excited atomic states.

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