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Morphological Features of the Copper Surface Layer under Sliding with High Density Electric Current

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Abstract. Conductivity and wear intensity of copper under the influence of dry friction and electric current with contact density higher 100 A/cm^2 are presented. It is shown that an increase in hardness and heat outflow from a friction zone leads to the reduction of wear intensity and current contact density increase corresponding to the beginning of catastrophic wear. Structural changes, such as the formation of FeO oxide and α-Fe particles in the copper surface layer, have also been found. It is observed that a worn surface is deformed according to a viscous liquid mechanism. Such singularity is explained in terms of appearance of high-excited atomic states in deforming micro-volumes near contact spots that lead to easy stress relaxation by local plastic shears in the vicinity of stress concentrators. In common this effect allows to achieve high wear resistance.

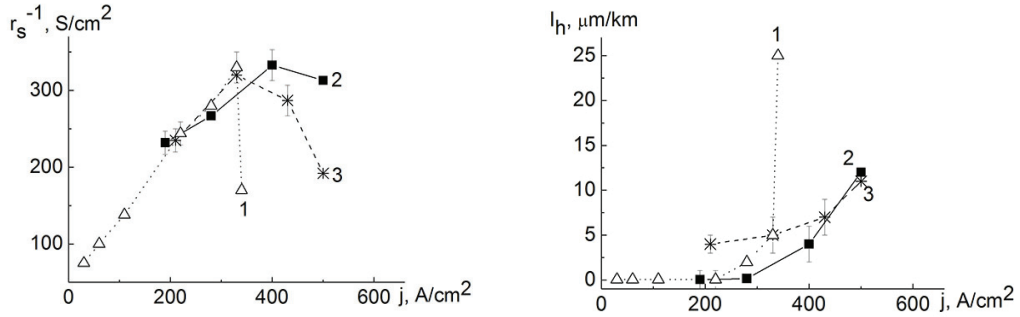
Keywords: high-excited atomic states, shear instability of material, wear intensity, deterioration of surface layer, phase composition, sliding electric contact, high current density

INTRODUCTION

A strong external frictional impact on a surface layer (SL) material leads to appearance of thermal and mechanical stresses in it. These stresses are relaxed by formation and movement of structural defects, in particular, by megaplastic deformation and formation of a fragmented or quasi-amorphous structure, or sometimes, by cracks [1, 2]. The low heat outflow from a friction zone may be one of the reasons for an increase in the friction surface temperature. It is possible when a specimen holder or a specimen itself have low heat conductivity. Another reason is a weak heat outflow to environment, for example, to vacuum or to rarefied gas. The difference between friction conditions and material initial state should result in different temperature fields and different scopes of SL plastic deformation. The heaviest stresses take place in contact spots. Microvolumes adjacent to contact spots should have a stable structure to make SL deterioration difficult. Microvolumes with high-excited atomic states may appear in these conditions. Such microvolumes can be deformed as viscous liquid [3] and provide easy plastic shear in SL.

One can often observe the formation of a structural change in the surface layer in sliding [4]. The material sliding under the high density electric current is an example of a strong external influence that causes SL plastic deformation and structural changes in SL [5, 6]. The structural state of SL sets the characteristics of the sliding contact. Generally, these characteristics also depend on other input parameters of a tribosystem, such as initial hardness of the material or the ability of a specimen holder to outflow the heat to environment.

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(a) (b)

FIGURE 1. Current dependence of specific surface electric conductance (a) and wear intensity (b) of contact of: the hard copper (HB_1 = 0.9 GPa) under weak heat outflow (curve *1*), the hard copper under good heat outflow (curve *2*), the soft copper (HB_2 = 0.4 GPa) under good heat outflow (curve *3*)

These factors influence the temperature of SL and its mechanical durability. Wear intensity is an integrated indicator of SL mechanical strength during the friction process. Generally, low wear intensity is caused by the high hardness and high plasticity of material [7].

It was observed earlier that high local plasticity of SL is a necessary condition for achievement of low wear intensity of steels while sliding with current collection [8, 9]. It is of scientific interest to observe this regularity in other materials while sliding in electric contact. It is convenient to carry out such research using copper in hardened and in annealed states. It is reasonable at the same time to get initial qualitative ideas about the influence of heat outflow to environment. Contact characteristics and sliding surface relief may serve as the indicators of the effect of these input tribosystem parameters on SL. A wear intensity value and an SL image taken as indicators of SL deformation should change with changing of hardness and heat outflow values. It is of interest to observe these changes and interconnection between them.

The aim of the present work is to obtain an initial idea of changes in contact characteristics and changes in surface layer parameters while changing copper hardness and the area of heat outflow in a friction unit.

MATERIALS AND METHODS

Copper specimens (99.95% Cu) of HB_1 = 0.9 GPa (hard copper) and HB_2 = 0.4 GPa (soft copper) hardness were used in the present paper. Hardness *(HB)* was defined using a Brinell hardness tester. The microstructure and worn surface were examined by optical microscopy (OM) applying the Neophot-21 microscope. The phase analysis of the sliding surfaces was carried on the DRON-3 X-ray diffractometer in cobalt radiation. Specimens were tested in conditions of sliding with current collection without lubrication at p_a = 0.13 MPa pressure and sliding velocity of v = 5 m/s. The test was run on the CMT-1 tribometer. A pin-on-ring type wear testing was used in this investigation. Sliding distance L for every friction regime was not lower 18 km. AISI 1045 steel having the hardness value of 50 HRC was used as a counterbody. Linear wear intensity was determined as $I_h = h/L$, where h is the change of a specimen height on sliding distance L. The contact current density j is found as $j = i/A_a$, where i is the contact current, A_a is the nominal (geometric) area of a tribocontact (A_a = 10 mm^2). The specimen holder had the heat outflow area of S_1 = 32 cm^2 (weak heat outflow) for HB_1 = 0.9 GPa copper in one case. In two other cases the holder heat outflow area had S_2 = 157 cm^2 value (good heat outflow) for HB_1 = 0.9 GPa and HB_2 = 0.4 GPa copper. Therefore both cases of weak heat outflow (S_1 = 32 cm^2) and good heat outflow (S_2 = 157 cm^2) were tested.

RESULTS AND DISCUSSION

Specific surface electric conductivity of sliding contact was written as $r_s^{-1} = j/U$, where j is the contact current density, U is the contact voltage drop and r is the contact electric resistance. The current dependence $r_s^{-1}(j)$ has a maximum (Fig. 1a), which depends on the SL structure state and heat area S change. This maximum corresponds to the inflexion of current-voltage characteristics and to the increase of wear intensity (Fig. 1b) that indicates the beginning of catastrophic wear.

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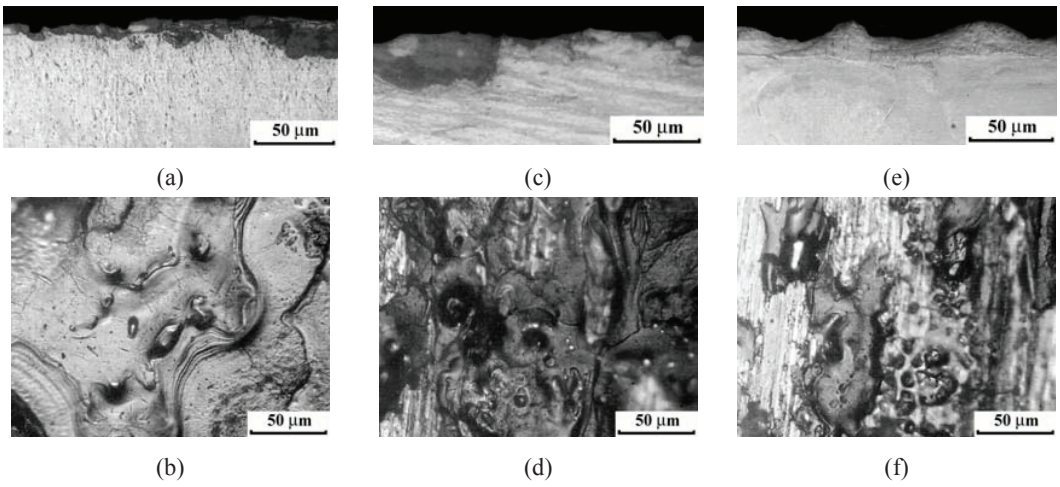


FIGURE 2. OM image of cross-section of worn surface (a) and the worn surface (b) of hard copper after friction at the weak heat outflow; OM image of cross-section of worn surface (c) and the worn surface (d) of hard copper after friction at the good heat outflow, OM image of cross-section of worn surface (e) and the worn surface (f) of soft copper after friction at the good heat outflow

Friction in these conditions is accompanied by the decrease of electric conductance with the increase of current density in contact. It is shown that the electric conductance r_s^{-1} in all cases of sliding has no significant difference at current density up to 320 A/cm^2 (Fig. 2a). The hard copper (HB_1 = 0.9 GPa) in the S_1 = 32 cm^2 specimen holder and the soft copper (HB_2 = 0.4 GPa) start to show catastrophic wear at the current density of $j \approx 330$ A/cm^2 (curves *1* and *3*). It is visible that the soft copper achieved lower $\partial r_s^{-1}/\partial j$ (curve *3*) under good heat outflow in comparison with $\partial r_s^{-1}/\partial j$ of the hard copper contact (HB_1 = 0.9 GPa), under weak heat outflow (curve *1*) in terms of catastrophic wear. The hard copper, being under good heat outflow, shows catastrophic wear at $j \approx 400$ A/cm^2 where $\partial r_s^{-1}/\partial j$ is low.

The hard copper shows rather low wear intensity with good heat outflow (Fig. 1b, curve *2*), but it has the sharp increase in intensity of wear (curve *1*) with weak heat outflow. Soft copper shows rather high wear intensity in the conditions of normal wear. However, catastrophic wear doesn't result in a sharp I_h increase (curve *3*). One can see that good heat outflow promotes high r_s^{-1} and low I_h at catastrophic wear.

Sliding of hard copper under weak heat outflow with a contact current density higher 200 A/cm^2 is accompanied by the structural change in the surface layer (Fig. 2a) and the sliding surface has signs of viscous liquid formation over all area of nominal contact (Fig. 2b). Structural changes under this surface happen at different depth and in different sectors of the nominal contact area (Fig. 2a). The same changes of SL appear in friction with good heat outflow (Figs. 2c and 2e). The sectors with signs of a viscous flow are formed on sliding surface of both hard and soft copper (Figs. 2d and 2f). However, the viscous flow in this case is observed over smaller sectors in comparison with the sectors shown in Fig. 2b. The soft copper surface layer undergoes the plastic deformation in relatively high depth (Fig. 2e). The main morphological feature of sliding surface of copper is the absence of adhesive interaction tracks at every regime of wear.

The layer having such friction induced structures (FIS) contains copper, FeO oxide and α-Fe particles transferred from a counterbody. One can see (Table 1) that $a_{\alpha\text{-Fe}}$ parameter of α-Fe lattice is slightly higher than known $a_{\alpha\text{-Fe}}$ = 0.2866 nm (X-ray/ASTM 6-696 Standard).

TABLE 1. Lattice parameters of the phases placed in friction induced structure layer and their comparative volume ratios after friction at catastrophic wear onset

Materials / Parameters	j, A/cm^2	$a_{\alpha\text{-Fe}}$, nm	a_{Cu}, nm	a_{FeO}, nm	$I_{\alpha\text{-Fe}}/I_{Cu}$	I_{FeO}/I_{Cu}
Cu (0.9 GPa, week heat outflow)	330	0.2876	0.3616	0.4306	0.13	1.3
Cu (0.9 GPa, good heat outflow)	400	0.2875	0.3617	0.4300	0.77	1.0
Cu (0.4 GPa, good heat outflow)	330	0.2879	0.3617	0.4308	0.55	0.5

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The a_{Cu} parameter of copper lattice corresponds to known a_{Cu} = 0.3615 nm (X-ray/ASTM 4-836 Standard). The oxide FeO lattice parameter is close to known a_{FeO} = 0.43070 nm (X-ray/ASTM 6-615 Standard). Volume ratios of phases can be compared on the basis of the $I_{\alpha\text{-Fe}}/I_{Cu}$ and I_{FeO}/I_{Cu} relations, where $I_{\alpha\text{-Fe}}$, I_{Cu}, I_{FeO} are integrated intensity of reflexes (110)α-Fe, (111)Cu and (200)FeO respectively (Table 1). One can see that rather large quantity of FeO oxide on the copper sliding surface is formed (or remains after sliding) in conditions of weak heat outflow. There is little FeO oxide on the sliding surface of soft copper. The lowest value $I_{\alpha\text{-Fe}}/I_{Cu}$ indicates the weakest transfer of steel particles from the counterbody to the copper surface at sliding under weak heat outflow.

One can expect that liquid emerging on contact surface will lead to an unlimited plastic flow of SL and high wear intensity. But usually more than half of atoms of surface layer materials based on copper or iron are connected in FeO oxide on depth higher than 200 nm after sliding on a steel counterbody [9].

Therefore, the FIS layer is hardened by FeO phase and the unlimited SL flow doesn't appear which causes low wear intensity. Besides a quasiliquid layer should have the small thickness and can not provide the unlimited plastic flow. The deformation of microvolumes placed near contact spots of hard copper like in case of a viscous liquid mechanism is one of the reasons for low wear intensity under low heat outflow. These conditions provide easy local shears in regions of stress concentrators allowing for the structure stability on macroscale. However, catastrophic wear can begin when the large amount of quasiliquid microvolumes appear causing the rush SL deterioration at week heat outflow. It is observed in cases of big $\partial r_s^{-1}/\partial j$ and big $\partial I_h/\partial j$ (Fig. 1). The formation of quasiliquid microvolumes and sharp changes in behavior of dependences $r_s^{-1}(j)$ and $I_h(j)$ are not observed in conditions of good heat outflow from a sliding surface.

Behavior of curves $r_s^{-1}(j)$ and $I_h(j)$ may be described in other words. It can be assumed that atoms of SL can be in a high-excited state, i.e. there are new possibilities for plastic deformation as relaxation process. It means that stresses in SL will relax well and I_h will be low. Low thickness of FIS layer (Figs. 2a and 2c) shows that SL deformation in normal wear doesn't propagate deeply owing to satisfactory relaxation of stresses by plastic deformation in thin SL. Insufficient hardening of FIS layer of soft copper by particles of iron and FeO oxide (Table 1) leads to a rather high scale of plastic deformation that is represented as the high thickness of FIS layer (Fig. 2e) and its rather high I_h. However, good heat outflow from a friction zone of soft copper is an obstacle to a sharp increase of sliding surface temperature and to a sharp increase of I_h at the beginning of catastrophic wear. Sliding surface temperature at weak heat outflow must be relatively high. It has to cause an easy plastic flow of big sectors of FIS layer that is shown in sharp increase of I_h at the beginning of catastrophic wear (Fig. 1). However the good copper plasticity provides rather low wear intensity comparing with different materials in these friction conditions [6, 9].

CONCLUSION

The stress relaxation in surface layer of copper happens due to plastic deformation under dry sliding on 1045 steel at every contact current density higher 100 A/cm^2. The deformation of a copper surface layer causes structural changes in it. The singularities of surface layer structure changes are shown in the first turn as the realization of a plastic flow according to the mechanism of viscous liquid, appearance of FeO oxide and the presence of α-Fe particles on a sliding surface. The weak heat outflow from a friction zone of hard (0.9 GPa) copper leads to formation of rather large quantity of FeO oxide in a layer of FIS and to sharp increase of wear intensity at the beginning of catastrophic wear at the contact current density about 330 A/cm^2. I.e. large quantity of FeO oxide increase the shear stability that lead to week stress relaxation and following easy surface layer deterioration. Catastrophic wear of soft (0.4 GPa) copper begins at the contact density of current about 330 A/cm^2 but the good heat outflow from friction zone is in obstacle to sharp wear intensity increasing. Hard copper under good heat outflow can form surface layer having quite optimal relation between hardness and plasticity that leads to satisfactory local shear instability in contact spots. Therefore catastrophic deterioration of surface layer occurs at the increased current density (about 400 A/cm^2).

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