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Dry Slipping Steel–Steel Contact at High Current Density

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Abstract—The behavior of steel 3 in dry slipping under the action of high-density electric current is studied. In these conditions, the surface layer undergoes plastic deformation; its temperature rises; and new phases and structural defects are formed. That gives rise to a layer of secondary structures. The basic factor disintegrating the surface layer is the contact current density. The mean contact temperature and layer thickness of the secondary structures increase with increase in current density. The variation in wear rate and electrical conductivity with change in contact temperature is studied. The wear rate depends linearly on the contact temperature in normal wear. Catastrophic wear appears as sharp increase in the wear rate and simultaneous decrease in the contact electrical conductivity at 500—600°C. The thickness of the layer of secondary structures is 50 μm in these frictional conditions.

Keywords: mean contact temperature, secondary structures, friction, wear rate, slipping-contact electrical conductivity

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Friction may cause considerable mechanical stress in microvolumes adjacent to the contact spot. Relaxation of this stress is often associated with plastic deformation and structural changes in the surface layer. A layer of secondary structures appears [1]. In the literature, this is also referred to, for example, as the third body [2], the frictional layer [3], and the friction-induced deformation layer [4]. Its thickness characterizes the penetration depth of plastic deformation into the frictional-contact zone. The output characteristics of the frictional system (wear rate, frictional coefficient, surface temperature, etc.) depend on the properties of the layer of secondary structures.

Severe friction appears, for example, at high pressure or high slip rate, with limited heat transfer from the frictional zone, in the absence of lubrication, and with the passage of electrical current through the contact spot. The mean surface temperature in those conditions may exceed 200°C [5–8]. It is of interest to determine the mean temperature of the slip surface, since the temperature affects the strength of the surface layer more powerfully than factors such as the load, the slip rate, or the number of loading cycles [7]. Known methods of assessing the mean contact surface temperature do not always present a satisfactory picture of the influence of temperature on surface failure in conditions of cyclic plastic deformation [5–10]. It follows from general principles that the wear resistance will decline with increase in mean surface temperature. However, we need better information regarding the mutual dependence of these characteristics and their relation with the layer thickness of the secondary structures. The model frictional pair may be the slipping electrical contact of steel 3 and steel 45, by analogy with [11]. In that case, the contact current density is the main factor responsible for the increase in temperature and the failure of the surface layer. Therefore, the dependence of the mean surface temperature on the contact current density is also of interest.

In the present work, we obtain an initial idea of the relations among the contact current density, the layer thickness of the secondary structures, the mean surface temperature, and the wear rate of steel 3 in slipping electrical contact without lubrication.

The model sample is produced from carbon steel 3 (Fe + 0.2% C) of hardness $HB = 2740$ MPa. Metallographic data regarding the cross section of the secondary structures is obtained on a Neophot-21 optical microscope. The wear rate of steel 3 and the electrical conductivity of the frictional zone are determined in conditions of slipping electrical contact without lubrication in the presence of 50-Hz alternating current, at a pressure $p = 0.13$ MPa and slip rate $v = 5$ m/s on an SMT-1 frictional machine in a pin-on-ring configuration (Fig. 1a). The counterbody is made of steel 45 (50 *HRC*). The slipping distance is 9 km at each current density. The linear wear rate is calculated as $I_h = h/L$,

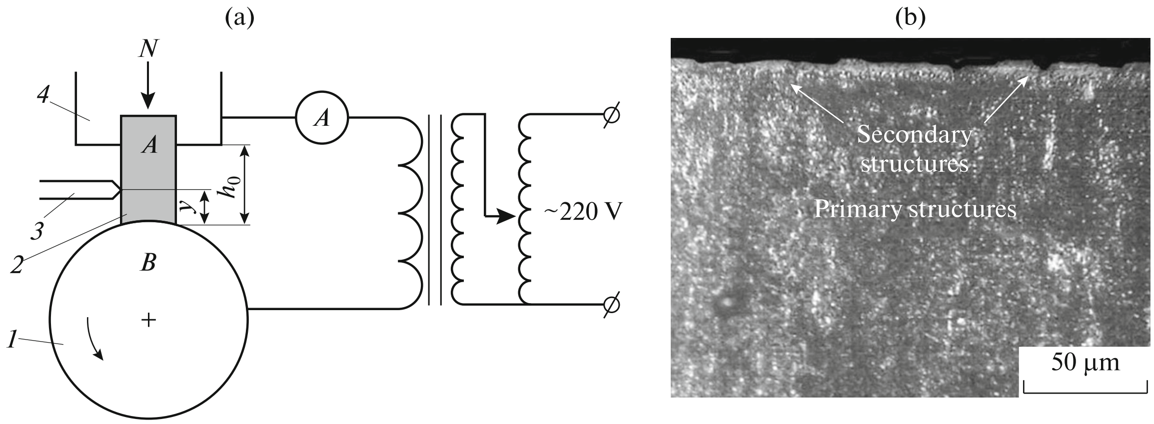

Fig. 1. Pin-on-ring test configuration: (*1*) counterbody (steel 45, 50 *HRC*); (*2*) sample (steel 3); (*3*) thermocouple; (*4*) sample holder (a); and primary structure of steel 3 in the cross section of the surface layer after slip with j = 120 A/cm^2 (b).

where h is the change in sample height at a slipping distance L. The contact current density is calculated as $j = i/A_a$, where i is the current passing through the specified contact area A_a.

The face A of the sample is in the same plane as surface B of the counterbody. The temperature distribution along the vertical axis of sample face A and at the counterbody around the contact zone is determined by means of a FLIR A655sc thermal-imaging system. Face A and surface B are coated in varnish to ensure the same thermal-emission coefficient. The actual temperature of any point is calculated by means of the readings of thermocouple *3* at a distance y = 2–3 mm from the contact surface. The thermocouple is attached to the sample by spot welding. Each temperature is calculated at a sample height $h_0 \approx 6$ mm. The mean temperature T_s of the sample's slip surface is greatest with a specific temperature distribution for each set of frictional conditions.

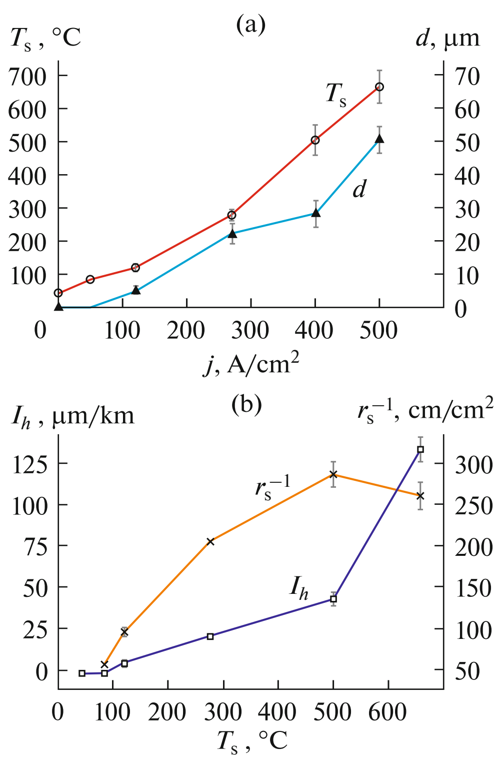

Fig. 2. Current dependence of the mean contact temperature T_s and layer thickness d of the secondary structures (a); and influence of T_s on the wear rate I_h and surface electrical conductivity r_s^{-1} (b).

One structural change in the surface layer is the formation of a white layer of secondary structures (Fig. 1b). The thickness of this layer increases with increase in the current density j (Fig. 2a). We see that slipping at j < 80 A/cm^2 does not lead to the formation of a pronounced layer of secondary structures. When j = 80–400 A/cm^2, the increase in the layer thickness d of the secondary structures is quasi-linear. However, when j > 400 A/cm^2, the rise in d is faster. The current dependence of the temperature T_s is also near-linear in the given range of j.

At T_s < 100°C, slip occurs without marked surface destruction. In other words, there is no wear, and $I_h = 0$ (Fig. 2b). Increase in T_s to 100—500°C leads to linear increase in I_h. The sharp increase in I_h at T_s > 500°C indicates the onset of catastrophic wear. At the same time, the surface electrical conductivity sharply declines: $r_s^{-1} = j/U$ at T_s > 500°C, where U is the contact potential difference and r_s is the contact electrical resistance.

Note that, when j < 80 A/cm^2, slip occurs with $I_h = 0$ [11]. This may be explained in that, in slip with j < 80 A/cm^2, low temperatures (T < 100°C) do not produce marked plastic deformation of the surface layer, since no layer of secondary structures is formed (its thickness d = 0; Fig. 2a). This means that plastic deformation of the surface layer only occurs before the strength limit is reached. In that case, the surface layer is in a strengthened state, with some constant concentration of deformational defects. Then microvolumes adjacent to the contact spot undergo elastic deformation, and the surface layer experiences loads in multicyclic fatigue, when structural defects accumulate slowly. The structural state of the surface layer may be regarded as stable. No disintegration of the surface layer is observed, as is evident at $I_h = 0$ with $j < 80$ A/cm^2 (Fig. 2b). These conditions are employed in practice, when the input parameters of the frictional system are selected so as to prevent structural changes in the surface layer during friction.

Normal wear is characterized by dynamic equilibrium between the formation and destruction of the layer of secondary structures [1]. In the present study, this corresponds to $j < j_c$ and $T_s < T_{sc}$. The layer thickness of the secondary structures is a contact characteristic. Therefore, it depends on the contact conditions. This is due to the difference in plastic strain rate of the surface layer in different frictional conditions. The appearance of wear in slip with $j > 100$ A/cm^2 indicates some instability of the surface structure on account of decrease in the plastic limit with increase in T_s above 100°C (Fig. 2a) and the onset of continuous formation of stress concentrators at different scale levels. Stress relaxation is due to local plastic shear in the vicinity of the stress concentrators [12]. The plastic strain of surface microvolumes in cyclic loading leads to the local accumulation of structural defects (dislocations, micropores, etc.) to some critical concentration. The stress relaxes on account of microcrack formation. Pores aggregate under the frictional layer and form subsurface microcracks parallel to the slip surface [13] but diverging at the contact boundary [14]. In that case, fragments of surface disintegration appear in the form of lobes. In the present work, increase in the temperature T_s leads to the appearance of iron oxides—mainly FeO [11]. That strengthens the layer of secondary structures but limits their capacity for stress relaxation by plastic local shear at small depths. Strengthening of the slip surface by oxides facilitates deformation at deeper layers and increase in the layer thickness of the secondary structures. The accumulation rate of structural defects increases accordingly in conditions of few-cycle fatigue. Likewise, the rate at which failure fragments of the secondary structures form and the overall wear rate increase (Fig. 2b).

Note that the current density $j = j_e$ at which catastrophic wear begins depends on the contact geometry, the size of the frictional pair, the rate of heat extraction, etc. Therefore, j_c may only characterize the wear resistance of the material in comparison with the j_c value for some other material. However, the temperature $T_s = T_{sc}$ at which catastrophic wear begins in some specified slip conditions characterizes the attainment of a limiting state of the surface layer in which the material is unstable with respect to macroshear and large volumes of secondary structures undergo unlimited plastic flow, as shown in [15]. We may assume that the temperature T_{sc} of a specific material (in the present case, steel 3) will be largely unchanged for slip in other conditions. Therefore, we may expect that the attainment of temperature T_{sc} in slip with low heat loss through the sample holder will lead to catastrophic wear of the surface layer when the current density j is less than $j_c \approx 400$ A/cm^2, as in the present work. Thus, the temperature T_{sc} is one of the basic factors controlling catastrophic wear of the surface layer. We may assume that, at $T_s > T_{sc}$, the rate at which micropores are formed in the surface layer corresponds predominantly to the formation of subsurface microcracks of critical length. Alternatively, the rate of oxide formation reaches some critical value sharply reducing the capacity for stress relaxation and sharply reducing the stability under macroshear.

The energy of the external perturbation released in the contact zone dissipates in the form of heat fluxes in the sample and counterbody and also in the form of energy expended in surface disintegration and the formation of wear particles. If the energy expended in surface disintegration (the work of failure) markedly exceeds the thermal energy, we would expect to find that the growth rate of T_s declines and the slope of the current dependence of T_s declines when $j > 400$ A/cm^2. However, the slope remains unchanged, which indicates that the work of surface failure is proportional to the energy of the external perturbation in the contact zone. We may expect that T_s is directly proportional to the heat flux entering the sample [9]. Therefore, the slope of the current dependence of T_s is also due to the current dependence of this heat flux. Constant slope of the $T_s(j)$ dependence in slip with $j > 270$ A/cm^2 (Fig. 2a) may be explained in that the heat flux entering the sample also depends linearly on j.

With the formation of oxides and structural defects and increase in T_s, the electrical resistivity of the secondary structures should increase and therefore the contact electrical conductivity should decrease. However, this cannot be proven experimentally. We see that the contact electrical conductivity r_s^{-1} increases with increase in T_s (on account of increase in j) in normal wear (Fig. 2b). This may be explained in that the basic current through the contact takes the form of electrical discharges. Hence, the basic contact area is current-conducting, regardless of the electrical conductivity at the contact spots.

Decrease in the contact electrical conductivity in catastrophic wear indicates the attainment of some critical concentration of structural defects, which are mainly concentrated at the slip surface. In that case, the rate of defect formation exceeds the ease of stress relaxation in the vicinity of these defects. We may expect that the stress should relax easily at $T_s > 500°C$ on account of plastic microshear in the layer of secondary structures. The lack of satisfactory stress relaxation may be explained in that the main defects at the slip surface are iron oxides, which form at a high rate [11].

CONCLUSIONS

The slip of steel 3 at steel 45 under the action of high contact current density (above 100 A/cm^2) without lubrication changes the structure of the surface layer: specifically, a layer of secondary structures is formed. The thickness of that layer increases with increase in the current density and is 50 μm in the case of catastrophic wear. At the onset of catastrophic wear, the layer thickness of the secondary structures begins to depend more sharply on the current.

The mean contact temperature increases with increase in the contact current density. When the slip surface is heated above 500°C, catastrophic wear appears. The wear rate depends linearly on the contact temperature in normal wear.

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