Russian Physics Journal, Vol. 52, No. 6, 2009

EFFECT OF THE PHASE COMPOSITION OF STEEL-BASED COMPOSITES ON THE ELECTRICAL RESISTANCE OF THE FRICTION ZONE UNDER CONDITIONS OF CURRENT COLLECTION

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The current-voltage diagram of the electric contact zone and the wear rate of sintered composites based on ball-bearing wastes steel (1.5% Cr*) and Hadfield steel (13%* Mn*) at sliding over quenched steel (0.45%* C*) are investigated with tin and lead incorporated in the friction zone. It is established that melting is accompanied by a significant decrease in the electrical resistance which causes the nonlinearity of the current-voltage diagram of the contact. An increase in the strength of the contact layers manifested through the increased wear resistance is simultaneously observed. Based on the Ohm law, it is qualitatively demonstrated that the nonlinearity is caused by the change of the true area of electrical contact. Results of analogous experiments for composites that do not contain lead or tin are presented. It is established that the electrical conductivity and the strength of the surface layer sharply decrease for such change of the phase composition.*

Keywords: sliding electrical contact, current-voltage diagram, electrical resistance of the friction zone, wear.

INTRODUCTION

Knowledge of the special features of surface layer destruction is necessary not only for simple deformation methods (tension, compression, bending, and torsion) but also for contact loading (friction, rolling, etc.). Friction as a method of mechanical energy introduction into a solid body has the strongest deforming influence accompanied by structural changes of the surface layer. Additional introduction of electric energy into the friction zone also engenders the corresponding deformation processes in the surface layer. The strength and the electrical conductivity of the surface layer in the friction zone are the most important characteristics taken into account in the design of sliding electrical contacts. It is well known that the main characteristics of the sliding electrical contact are the contact electrical resistance and the wear resistance. One of the methods of obtaining good conductivity in the friction zone is the application of materials with low specific electrical resistance. Another method is based on an increase in the area of the true electrical contact by the increase of the geometrical area of the sliding electrical contact or by the incorporation of solid or liquid current-conducting lubricants in the friction zone. Graphite, molybdenum disulfide, or low-melting metals (lead, tin, etc.) are used as solid lubricants. It is considered that the low-melting materials incorporated into the initial structure of the composite spread into the contact zone during friction and form a quasi-amorphous lubricating metal film [1]. It is also assumed that in some friction regimes, the low-melting materials will spread into the contact zone in large volumes [2], but comprehensive studies have not yet been carried out, and these composites have found no practical application. This is due to the lack of methods for obtaining high mechanical strength of the materials and the necessity of their sliding with increased current density at which lubrication is evaporated and a severe electric erosion wear of the material and copper counterbody occurs. In addition, the synthesis of a high-strength material containing low-melting metals is difficult technologically. However, the development of these materials and the study of the

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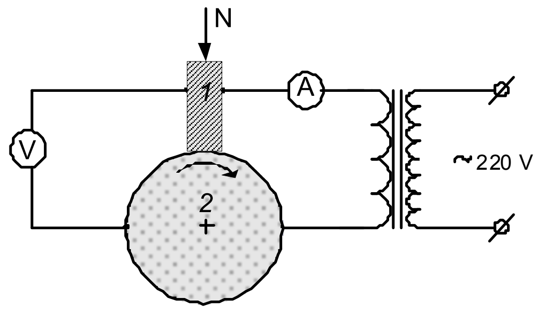

Fig. 1. Shaft-shoe triboloading scheme at sliding current collection. Here *1* denotes the examined material (specimen) and *2* denotes the counterbody (steel 45, 50 HRC).

possibility of their sliding at current collection in the presence of the liquid phase in the friction zone are of great scientific and practical interest. Scientific principles of synthesizing these materials have not yet been developed, and they are determined experimentally.

The small area of the true electrical contact with insufficient or completely absent current-conducting lubricants engenders high local current density that destroys the friction surface due to bridge electric erosion or adhesion to the counterbody, that is, the wear process is intensified. These phenomena are accompanied by the formation of electric discharges in the friction zone. Therefore, sparking during sliding at current collection can be considered as an indicator of a higher rate of material wear in the friction zone.

Nowadays the materials used for sliding electrical contacts are based, as a rule, on copper or iron in combination with low-melting elements. Their operation does not lead to the formation of the liquid phase in the friction zone. However, the design of sliding high-current contacts requires that the electrical resistance of the friction zone in the presence of the liquid phase to be considered obligatory. For this purpose, the current-voltage diagram of the friction unit in which melting occurs must be determined and the strength of the contact layer must be investigated. The wear intensity is a measure of the strength of the surface layer in friction. In experiments it is convenient to use the composites based on ball-bearing wastes steel (1.5% Cr) or Hadfield steel (13% Mn) whose sliding electrical contact has satisfactory strength of the material in the friction zone [3].

In the present work, the wear intensity of model composites based on ball-bearing wastes steel (1.5% Cr) or Hadfield steel (13% Mn) at sliding current collection is determined and the current-voltage diagram of the friction zone containing lead and tin is studied.

MATERIALS AND EXPERIMENTAL PROCEDURE

The composites comprised Cu–10 vol.% graphite–70 vol.% Me, where Me denotes Hadfield steel (H13) or ball-bearing steel (ShKh15) reprocessed from grinding wastes. The steel particle sizes did not exceed 100 μm. Specimens were fabricated by single pressing of a powder mixture at a pressure of 550 MPa and sintering in vacuum at a temperature of 1100ºC for 2 h. The bending strength was determined using an Instron-1185 test machine. Metallographic studies were performed with a Neophot-21 optical microscope. The specific electrical resistance of the composites was determined by the ammeter-voltmeter method. The porosity was measured by the method of hydrostatic weighing on an analytical balance.

Tribotechnical tests were performed at sliding current collection without lubrication with a sliding velocity of 2 m/s at a pressure of 0.13 MPa using an SMT-1 friction machine and the shaft-shoe loading scheme (Fig. 1) with the counterbody made of steel 45, 50 HRC (Fe–0.45C–0.3Si–0.65Mn–0.3Cu). The friction path was no shorter than 9 km. Running of the electric current through the tribocontact was provided by the application of ac voltage with a mains frequency of 50 Hz. Tin and lead were incorporated into the friction zone by deposition of Pb–Sn alloy coating with

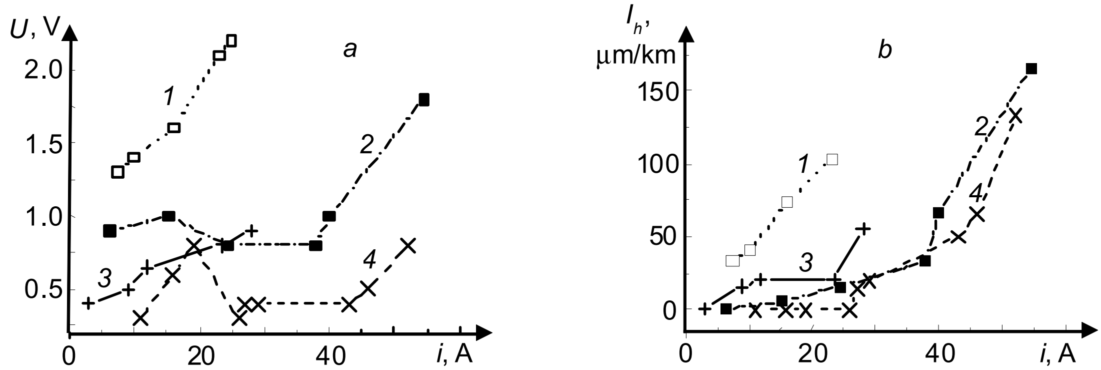

Fig. 2. Current-voltage diagram of the friction zone (*a*) and wear intensity (*b*) of the steel-based composites. Here curve *1* is for Cu–graphite–H13, curve *2* is for Cu–graphite–H13 + (Pb–Sn), curve *3* is for Cu–graphite–ShKh15, and curve *4* is for Cu–graphite–ShKh15 + (Pb–Sn).

thickness of 0.5 mm on the lateral surface of the model composites. The linear wear intensity I_h was defined as a ratio of the change in the specimen height (in μm) to the friction path (in km).

RESULTS AND THEIR DISCUSSION

The electrical resistance of any arbitrary element of an electric circuit can be judged from its current-voltage diagram (CVD). From Fig. 2*a* it can be seen that the friction zone of the composites without lead or tin shows a linear dependence of the contact voltage on the current. The slope of this dependence $\frac{dU}{di}$ characterizes the electrical resistance of the friction zone, and its change demonstrates that some processes proceed in it. The slope will increase when oxides are formed in this zone. For definite current values, the friction surface can be completely covered with oxides, and the conductivity is provided only by discharges. In this case, $\frac{dU}{di}$ takes great values [4]. Discharges in the friction zone of the sliding electrical contact cause the wear rate of the friction pair to increase and demonstrate insufficient electrical conducting area of the current collection; therefore, this makes one to search for methods of its increase. For this purpose, we incorporated the Pb–Sn alloy into the friction zone. As can be seen from Fig. 2*a*, the CVDs of the electrical contact for both composites have segments with negative slopes. Such CVD features are also characteristic of semiconductor thermal resistors, arc discharges, and other conductor types. The CVD nonlinearity can also be caused by the processes proceeding inside the electrical circuit element and can be explained with allowance for the parameter of the process responsible for this nonlinearity.

According to the Ohm law ($U = ir$), we can write

$$\frac{dU}{di} = r + i\frac{dr}{di}. \tag{1}$$

The derivative $\frac{dr}{di}$ causes the CVD nonlinearity and can have "+" or "–" sign. In the zone of sliding electrical contact, the current can run through spots of direct metal contact, through air gaps by means of discharges, and through the current-conducting lubricant. The metal contact exists always and is taken into account in r entering Eq. (1). At some currents, additional conductivity can be caused by discharges given that the metal contact and current-conducting lubrication do not provide the required current-conducting area s being the parameter which causes the CVD

TABLE 1. Physical and Mechanical Properties of Sintered Composites

Composition/Properties	Brinell hardness HB, MPa	Bending stress $\sigma_{b.s}$, MPa	Porosity Π, %	ρ, μΩ·m
1) Cu + 10 vol% graphite + 70 vol.% ShKh15	1722	920	11	0.24
2) Cu + 10 vol.% graphite + 70 vol.% H13	1530	500	13	1.0

nonlinearity in the zone of sliding electrical contact. Therefore, the CVD nonlinearity can be represented more vividly if we formally introduce the area of the current-conducting contact *s* into Eq. (1):

$$\frac{dU}{di} = r + i\frac{dr}{ds}\frac{ds}{di}. \tag{2}$$

The sign of expression (2) is determined by the value and sign of the second term. The derivative is $\frac{dr}{ds} < 0$; therefore, we consider only the sign of the dependence $s(i)$. When the contact area increases, $\frac{ds}{di} > 0$. This is observed when the liquid Pb–Sn alloy spreads over the friction zone, a dissipative structure is formed in the surface layer, electrical discharges are initiated, a phase transformation occurs, or any other additional conductivity arises thereby decreasing the electrical resistance. This can be considered as an increase in the current-conducting area. The main reason for the decrease of the electrical resistance of the friction zone with increasing current in Fig. 2*a* is melting of the Pb–Sn alloy which spreads into the friction zone and increases the current-conducting contact area. The increase of the electrical resistance for currents exceeding 35 A is caused by the decreased content of the Pb–Sn alloy in the contact zone and formation of non-conducting oxides on the surface layer, which is equivalent to the decrease of the contact area. In this case $\frac{ds}{di} < 0$, and the second term of Eq. (2) becomes positive.

It should be noted that the electrical resistance of the contact zone with low-melting components is smaller than that without these components for the entire range of current variation. This means that a certain amount of lead and tin is always present in the friction zone in the form of a quasi-amorphous film. In general, the electrical resistance of the contact is higher for materials with higher specific electrical resistance. Therefore, the composite material based on steel H13, having a higher specific electrical resistance than the composite based on steel ShKh15 (Table 1), forms the contact zone with a higher resistance (see Fig. 2*a*).

The capability of forming large electrical contact area is caused by the low hardness of tin and lead that simultaneously provide the required shear instability of the material in the friction zone and play the role of lubricants. As a result, the wear intensity decreases (see Fig. 2*b*), and the difference between the wear resistances of both composites becomes small. In the presence of tin and lead, no electrical discharges are generated in the entire range of current variation, which demonstrates sufficiently large area *s* in the examined friction regimes. The increase of the shear stability of the surface layer and, in particular, the absence of melting elements in the friction zone initiate electrical discharges that increase the wear rate of the friction surface (see Fig. 2*b*). This demonstrates that the high hardness of the composites (see Table 1) does not allow a sufficiently large area *s* to be formed; therefore, the material with a high hardness cannot provide a low electrical resistance in the friction zone. However, high hardness provides a high strength of the surface layer; therefore, technology for synthesizing composites with a metal core having a high hardness and a low-melting phase inside it must be found.

Based on the results obtained, we can conclude the following:

1. Lead and tin incorporated into the composition of the current collecting material decrease the electrical resistance in the friction zone of the sliding electrical contact.

2. Melted materials in the friction zone of the sliding electrical contact cause the nonlinearity of the current-voltage diagram that allows the electrical resistance of the entire tribocontact to be decreased.

3. Sliding in the liquid phase allows the high mechanical strength of the surface layer to be retained thereby providing the high wear resistance of the tribocontact.

This work was partly supported by the Russian Foundation for Basic Research (grant 06-08-00775-b) and by Project 3.6.1.2 of Fundamental Research Program 3.6.1 of the Siberian Branch of the Russian Academy of Sciences.

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