Characteristics of dry sliding electric contact of sintered metal based composites at catastrophic wear onset

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Abstract. Dry sliding of powder metal based composites was carried out against steel counterbody under electric current of density higher 100 A/cm². It was shown that the surface layers were transformed into tribolayers under these sliding conditions. An optical image of the possible deterioration of the tribolayer and a method for estimation its specific electrical resistance were presented. It was established by X-ray phase analysis that the tribolayers contained the initial phases and, sometimes, FeO. The relatively low electrical resistance of the tribolayer and the formation of FeO on the sliding surface corresponded to low wear of the composite without alloying metals in the primary structure. The tribolayers of composites with dissolved metals in the primary structure had high specific resistance, were not able to form FeO on their sliding surfaces and had strong deteriorations. This manifested itself as high wear. At the same time a manifestation of low electrical conductivity of the contact was observed. The catastrophic wear of both types of composites began at nearly equal power on the contact spots but at different current densities. It was concluded that the high wear was due to the absence of FeO on the sliding surface and weak relaxation of stresses in the friction zone of composites containing dissolved metals in their base.

1. Introduction

It is known [1] that the main loads during friction occur in contact spots. It is evident that the high strength of the surface layer (SL) is achieved in the case of elastic deformation of microvolumes adjacent to contact spots. Then SL is deteriorated due to multi-cycle fatigue and the corresponding wear is low. This condition is most easily fulfilled when applying lubricants or SL modifications by various hardening technologies. Creating a stable SL structure is the main goal of these procedures. However under severe friction regimes inevitable plastic deformation of microvolumes occurs in the vicinity of contact spots and SL is deteriorated due to low-cycle fatigue. Then the deterioration rate is quite high and strong wear is realized.

It is of interest to find ways to reduce the SL deterioration rate under severe friction. Providing easy relaxation of stresses in a metal due to local plastic deformation in the zone of stress concentrators is the most general principle of decreasing the fracture rate [2,3]. Application of this principle to reduce...
wear requires setting high ductility of micro-volumes adjacent to contact spots. Then some dynamic stability of the SL structure can be realized and wear should be minimal. These cases were observed in dry sliding of some metallic materials under electric current of high density [4]. The electric current passing through the contact spots causes the activation of plastic deformation of microvolumes in SL and contributes to an increase in the wear rate. The limiting SL state appears at some critical current density \( j = j_c \), and catastrophic wear begins. Normal wear occurs in sliding with \( j < j_c \).

It is obvious that \( j_c \) depends on the material primary structure. In addition \( j_c \) depends on the power of deteriorating factors on the contact spots. These factors are determined by the tribosystem input parameters (sliding speed, contact pressure, contact geometry, environmental composition, etc.). Sliding under electric current [4,5] or without current [6,7] often leads to structural changes in SL and to the formation of a tribolayer. Therefore \( j_c \) also depends on the structure and strength of the tribolayer. High strength of the tribolayer is manifested as a low wear rate. It should be expected that a tribolayer having high strength will begin to deteriorate catastrophically at high \( j_c \). The friction power values on the contact spots under catastrophic wear onset may be of some interest. Knowledge of the values of these contact characteristics can be useful in searching of SL deterioration regularities under external energy impact. Powder composites on metal bases of different compositions can serve as model materials for research in this direction.

The aim of this work is to study the relationship between the primary structure, changes in the structure of surface layers and tribological power on the contact spots of metal based composites in sliding under electric current collection of high density.

2. Materials and methods

Powder composites had the compositions presented in Table 1 where HS denoted the Hadfield steel (13% Mn). Composite of composition TiC-30% Cu-20% HS was produced by high temperature combustion method and served as the base of composite 2. Sintering was carried out at \( T = 1100^\circ\text{C} \) for 2 hours in vacuum. Quality phase compositions of their sliding surfaces and lattice parameters were defined using X-ray diffractometer DRON-3 in the radiation of Co Kα. Optical images of the surface layers were obtained using optical microscope Neophot-21. Brinell hardnesses \( HB \) of composites, microhardnesses \( H_v \) of their tribolayers, specific electrical resistivity \( \rho \) of composites, porosity \( P \) of composites and their thermal conductivities \( \lambda_2 \) are determined by standard methods.

| Composition, vol.%/characteristics | \( HB \), MPa | \( H_v \), MPa | \( \rho \), \( \mu \Omega \cdot \text{m} \) | \( P \), % | \( \lambda_2 \), W/(m·K) | \( \zeta_2 \) | \( d_{\text{Cu}} \), nm | \( d_{\text{FeO}} \), nm |
|----------------------------------|--------------|--------------|----------------|------|----------------|--------|--------------|--------------|
| 1. Cu-10% Gr-70% HS             | 1.67         | 4.85         | 1.0            | 13   | 24             | 0.4    | 0.360        | —            |
| 2. Cu-10% Gr-70% (TiC, Cu, HS)  | 1.14         | 4.47         | 0.32           | 13   | 28             | 0.43   | 0.362        | —            |
| 3. Cu-10% Gr-70% Fe             | 1.22         | 3.96         | 0.16           | 10   | 72             | 0.64   | 0.362        | 0.430        |

Tribotechnical characteristics were determined in dry sliding under alternating current (50 Hz), contact pressure \( p = 0.13 \) MPa, sliding speed \( v = 5 \) m/s using tribometer SMT-1 according to the standard “pin-on-ring” scheme (figure 1a). AISI steel 1045 having a hardness value of 50 HRC was used as the counterbody. Sliding distance \( L \) for every friction regime was 9 km. Linear wear intensity was found as \( I_w = \frac{h}{L} \) where \( h \) is a change of the specimen height along sliding distance \( L \). Contact current density \( j \) was found as \( j = \frac{i}{A_o} \) where \( i \) is a contact alternative current passing through nominal (geometric) area \( A_o \) of tribococontact \((A_o = 10 \) mm\(^2\)).

Wear can also be characterized by wear rate \( I_w = V/A \), where \( V/A \) is the ratio of deteriorated SL volume \( V \) to the expended work \( A \) of the friction force (or external forces). The wear rate can be converted to the form \( I_w = vI/q \) where \( q \) is the specific surface friction power \((q = Af/A_o)\) and \( r \) is a sliding time. In sliding with current collection \( A = fpA_o\sqrt{t} + iUt \) where \( f \) is the coefficient of friction, \( U \) is the contact voltage drop. Hence \( q = fpv + j/r_s^{-1} \) where \( r_s^{-1} \) is the specific contact surface conductivity \((r_s^{-1} = j/U)\). The \( I_w \) change is characterized mainly by changes in the parameter \( I_w/q \) which
should be considered as an indicator of the ability of the surface layer to deteriorate under the influence of a single friction power with current collection. The $A/V$ parameter is the specific work of the SL deterioration.

The specific power of the external impact on the specimen contact spots may be represented as $q_r = \zeta_2(fvN + U_1)/A$, where $\zeta_2$ is a part of friction power directed to the specimen, $A_r$ is the real contact spots area, $U$ is contact voltage drop, $i_1$ is the current at the contact spots. The coefficient $\zeta_2$ is sometimes calculated by the Block or Sharron formula, or by other formulas. All these formulas are very approximated but for a comparative description it seems convenient to apply the Block's formula because of its simplicity, i.e. $\zeta_2 = \lambda_2/\lambda_1$. One can see that such equation may be fulfilled only at equal temperature gradients directed to the specimen and to the counterbody. It was taken into account that wear is caused by plastic deformation of microvolumes adjacent to contact spots. This leads to the formation of the real area $A_r = N/\text{HB}_1$ ($N$ is the normal force (figure 1), $\text{HB}_1$ is the Brinell hardness of the surface layer or the tribolayer) [1,8]. In the present work it was assumed that $\text{HB}_1 = H'_u$ (tribolayer microhardness). Then $q_r = \zeta_2(fv + i_1 U/N)H'_u$.

In the present work it was proposed to estimate the specific electrical resistivity $\rho_1$ of a tribolayer using the Holm formula for restriction resistance $r_1 = 0.25(\rho_1 + \rho_2)/an$ where $a$ is the contact spot radius, $n$ is the contact spot quantity, $\rho_2$ is the specific electrical resistivity of the counterbody [8]. The parameters $a$ and $n$ are related by the expression $A_r = \pi a^2 n$. This implies $\rho_1 = 4r_1(A_n/\pi)^{0.5} - \rho_2$ or $\rho_1 = 4r_1(NH'_u\pi)^{0.5} - \rho_2$. Estimating the $\rho_1$ value does not require knowing the exact number $n$ of contact spots. At low pressure and relatively high hardness of the tribolayer we can assume that it forms the minimum number of contact spots $n = 3$.

![Figure 1. Schematic representation of pin-on-ring test machine structure (a); worn surface and cross-section of the surface layers of the composite Cu-Gr-70% HS (b) (Gr = graphite).](image)

3. Results

Dry sliding of metal composites under electric current of density higher 100 A/cm$^2$ causes often structural transformation of the surface layer and a tribolayer is formed. The presence of adhesion and low ability to relax stresses in the tribolayer leads to the appearance of structural defects of a high scale level (cracks, voids of the tribolayer scale, figure 1b). This type of the tribolayer deterioration is observed as a rule in sliding of materials with a complex primary structure where there are intermetallic compounds, or a high concentration of alloying elements, etc. This leads to a low electrical conductivity of the contact $r_{e-1}$ and to high wear intensity $I_h$ (figure 2). Usually the specific contact surface conductivity $r_{s-1}$ increases at $j$ increasing (figure 2) to any maximum $r_{s-1}$. This maximum appears at some current density $j_c$, when catastrophic wear begins and the wear intensity $I_h$ sharply increases at $I_h = I_{hc}$ (figure 2b). The contact characteristics $j_c$, $r_{s-1}$, $I_h$, and $I_{hc}$ depend on the primary structure and can serve as indicators of the limiting stability of the surface layers of the composites.
The absence of complexity in the primary structure of composite 3 is one of the reasons for the appearance of a relatively high electrical conductivity $r_s^{-1}$ of the contact in comparison with $r_s^{-1}$ of the other composites having solid solutions in the primary structure (figure 2a). The high conductivity $r_s^{-1}$ of composite 3 corresponds to its low wear intensity (figure 2b). This indicates that the primary structure without solid solutions will provide high shear stability of the tribolayer at the macroscale level of plastic deformation during friction. (The composite number in the text corresponds to the composite number in the Table 1).

The existence of solid solutions in the primary structure promotes the formation of tribolayers with relatively high specific electrical resistances (figure 3a). It is also seen (figure 3b) that deterioration indicator $I_h/q$ of the tribolayer of composite 3 is relatively low. This indicates a higher deterioration energy of this tribolayer, i.e. its higher strength at a higher current density compared with that of composites 1 and 2. Low $\rho$, high $\lambda$ of the primary structure and low $\rho_1$ of tribolayer of composite 3 do not cause a decrease in the power $q_r$ on the contact spots compared to $q_r$ in the contacts of other composites (figure 3c). This may be due to high $\zeta_2$, i.e. this is conditioned by high $\lambda_2$. At the same time this is additional proofing of the assertion that the high strength of the tribolayer is due to the simplicity of the primary structure. We can assume that weak dependence of $q_r$ on the primary structure is a general regularity of tribolayers deterioration of graphite-containing composites in sliding with $q_r < 1.5$ MW/cm$^2$.

The output parameters of the tribosystem with current collection ($r_s^{-1}$, $I_h$, $I_h/q$, $q_r$, $f$, $H_\mu$, $\rho_1$) should strongly depend on the phase composition of the tribolayer. It is shown (figure 4) that XRD pattern of SL of composite 3 contains FeO peaks. This corresponds to low values of $I_h$ at high $j$. Other
composites are not able to form FeO on their sliding surfaces. This leads to increasing of the limiting values of \( I_h \). The ability to form FeO on a sliding surface is the main feature of some metallic materials in sliding with a current collection. It is possible that the concentration of FeO will increase at approaching to the sliding surface. XRD pattern of composites surface layers contain also peaks of initial metal phases. One can assume that the tribolayer is a composite where the initial phases serve as a matrix and FeO is a solid filler. The copper lattice parameter may slightly differ from the standard parameter \( a_{Cu} = 0.3615 \text{ nm} \) (X-ray/ASTM 4-836 Standard). This indicates the appearance of a solution of metal in copper during sintering or in sliding.

**Figure 4.** XRD pattern of sliding surfaces at the onset of catastrophic wear of composites.

4. Discussion

The formation of FeO on a sliding surface causes the hardening of the tribolayer and reduces the adhesion in the contact. Therefore the low wear characteristics will be observed in sliding of metal materials capable to form and to save an oxide film on their sliding surface. In this case the oxides play the role of a lubricant. Micro- and nanoparticles of oxides on a sliding surface experience the main loadings that are dissipated into the surrounding metal phases. These initial metal phases play the role of a matrix. Effective stress relaxation in the matrix causes satisfactory SL shear stability and high wear resistance is observed. Stress relaxation usually occurs due to plastic micro-shears in the vicinity of stress concentrators arising from the application of a load. Light plastic flow occurs in pure metals. In addition pure metals have a quite high thermal conductivity comparing with metal solutions. This leads to the appearance of low temperature gradients in the contact zone and, correspondingly, to low mechanical stresses in the contact spots.

Pure metals have quite low specific electrical resistance. This provides a high electrical conductivity of the contact. The composite tribolayer of composite 3 has a metal matrix of pure copper and iron, which provide satisfactory relaxation of stresses, a low temperature gradient on a sliding surface and high electrical conductivity of the contact. These factors combined with FeO in the tribolayer of composite 3 contribute to the manifestation of satisfactory main characteristics of the contact, namely, the wear intensity \( I_h \) and electrical conductivity \( r_{-1} \) of the contact. The metal matrices of tribolayers of composites 1 and 2 contain dissolved metals, which cause a decrease in ductility and the low ability to relax stresses due to plastic micro-shears. Solid solutions of metals lead to a decrease in thermal and electrical conductivity of initial structures. In addition, the absence of FeO on the sliding surface causes adhesion. This means that only these factors lead to a noticeable increase in \( I_h \).
(figure 2), because powers $q_r$ on the contact spots are approximately equal each other (figure 3c). It is possible that the equality of these powers indicates a certain limit and its excess means catastrophic wear of a metal composite with any primary structure. It is evidently that many composites will exhibit catastrophic wear at lower $q_r$. It indicates that some new materials, for example, high-entropy materials, are fundamentally inapplicable for satisfactory dry sliding with current collection.

It should be mentioned that the specific electrical resistance $\rho_1$ of the tribolayer is not a physical characteristic, because $\rho_1$ depends on hardness (hardness is not a physical property) and on the contact interaction character. Therefore only the possible values of $\rho_1$ are shown in figure 3. But these values are useful for comparative analysis. It is seen also that high $\rho$ corresponds to the formation of tribolayer having high $\rho_1$ (Table 1). The $\rho_1$ values are close to the specific resistance values of industrial current collection graphite composites. In the present work some wear-resistant conductive composites having high $\rho$ (for example, TiC-Cu-HS composite, surfacing materials based on cobalt (Stellite) or nickel (Ni-Cr-B-Si)) were tested in sliding under electric current. These materials manifested sliding only with $r_s^{-1} = 0 \text{ S/cm}^2$. Obviously, zero wear was obtained under these conditions but such contact is not of interest. This indicates the existence of a certain limiting value of $\rho$ which can serve as a criterion for unsuitability at creating of materials for dry sliding current collection with a high current density.

5. Summary
Dry sliding of metal powder composites against steel counterbody under electric current of density higher 100 $A/cm^2$ causes the activation of surface layer plastic deformation. Therefore it forms tribolayers containing initial phases. Besides it is formed FeO in tribolayers of composites having no solid solutions in initial phases. Such structure of tribolayer provides low specific electric resistance of tribolayer and satisfactory relaxation of mechanical stresses in the vicinity of stress concentrators appearing in the contact spots. These factors lead to the low wear intensity. This indicates the inappropriateness of the use of alloyed materials for dry sliding under high density electric current. Catastrophic wear will be manifested at power of external impact lower 1.5 MW/cm$^2$ on contact spots of every metal composite.

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