Modification of contact surfaces of steel based materials in dry sliding under electric current of high density

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Abstract. The purpose of the work was to study the interrelation of primary structure and wear resistance as well as to receive the initial ideas on contact features and surface layer deterioration in dry sliding against steel under electric current. The tribological behaviour of bearing steel and Hadfield steel (13% Mn) as well as the behaviour of composites on their bases was studied under electric current of high-density. Using X-ray phase analysis it was shown that the electrical current caused a modification of the surface layer of bearing steel and bearing steel sintered composite due to the formation of tribolayer and sliding surface melting in dry sliding against quenched AISI steel 1045. The formation of FeO in the tribolayer was observed also. This contributed to hardening of the sliding surface and to the realization of low wear intensity. Hadfield steel and a sintered composite based on it were capable of forming a tribolayer, where there was a low content of FeO on the sliding surface. This led to a high wear rate due to adhesion. The low thermal conductivity of Hadfield steel based materials should be considered as another reason for the rapid deterioration of their tribolayers.

1. Introduction

Wear intensity is the main indicator characterizing the surface layer strength under sliding contact of two bodies. Wear can be reduced by optimizing the input parameters of a tribosystem (contact pressure, composition of materials, sliding speed, etc.) [1] and, in particular, by modification of a surface layer or material initial structure [2,3]. In this case, the pressure on the contact spots does not exceed the yield strength of the surface layer material. However, study of the change of the surface layer structure in the case of its plastic deformation is of the greatest interest when pressure on the contact spots, as a rule, exceeds a yield strength of material and it deteriorates owing to low-cyclic fatigue. In these conditions the low wear rate can be achieved due to plasticity of material (but not due to accumulation of structural defects) or when the supplied energy is dissipated through heat outflow, as well as owing to other factors [4].

The surface layer can be loaded, for example, by high pressures, sliding speed, electric current density, etc. The dry sliding of metal materials under current collecting is usually carried out under electric current density lower 60 A/cm\textsuperscript{2} [5]. In this case the surface layer, as a rule, does not undergoes plastic deformation. It is of interest to study the influence of material structure on wear resistance under sliding surface plastic deformation at electric current density higher 100 A/cm\textsuperscript{2}. The
tribotechnical steels can serve as model materials having evident differences in primary structure and properties, for example bearing steel and Hadfield steel (13% of Mn) and as well composites based on these steels of composition Cu-graphite-steel.

The aim of this work is to study interconnection between the primary structure and wear resistance and to obtain initial ideas of features of contact and deterioration of surface layer in dry sliding against steel under electric current of contact higher 100 A/cm².

2. Experimental details

The composition and properties of the applied materials are given in the table 1. Cast bearing steel (BS) and cast Hadfield steel (HS) were subjected to standard heat treatments. Composite of composition Cu-10%Gr-70%BS was based on bearing steel obtained by recycling of grinding wastes of ball bearings production [6]. Composite of Cu-10%Gr-70%HS had the powder Hadfield steel as the base, where Gr denotes graphite. Composites were sintered in a vacuum at 1100°C for 2 hours. Brinell hardness HB, porosity P, specific electrical resistance ρ, thermal conductivities of the material λ and bending strength point σ were determined by standard methods. The friction test was carried out without lubricant under alternating current (50 Hz), contact pressure of p=0.13 MPa, sliding speed of v=5 m/s using an SMT-1 tribotester using the "pin-on-ring" scheme. The sliding distance for each test was 9 km. The linear wear intensity was determined as I₈ = h/L, where h is the change in the sample height along the sliding distance L. AISI steel 1045 (50 HRC) served as a counterbody. The contact current density was defined as j=i/Aw where i is the current passing through a nominal contact area Aw.

| Table 1. Mechanical and physical properties of materials. |
|----------------------------------|
| Composition/properties | Hardness HB (GPa) | Porosity P (%) | Specific electric resistance ρ (Ωm) | Thermal conductivity λ (W/m·K) | Bending strength σ (MPa) |
|--------------------------|-----------------|---------------|---------------------------------|---------------------------------|--------------------------|
| 1. Bearing steel (Fe-1,2%C-1,5%Cr) | 63 HRC | - | 0,29 | 41 | 2000 |
| 2. Hadfield steel (Fe-1,2%C-13%Mn) | 2,4 | - | 1,1 | 11 | 700 |
| 3. Cu-10%Gr-70% BS | 1,72 | 12 | 0,24 | 53 | 905 |
| 4. Cu-10%Gr-70% HS | 1,7 | 13 | 1,0 | 24 | 440 |

3. Results

The wear intensity I₈ increases nonlinearly with increasing of current density j in the normal wear mode for all studied materials. Catastrophic wear manifests itself in the form of sharp wear intensity increase of the studied materials. It is seen (figure 1,a) that catastrophic wear of bearing steel, Hadfield steel and a composite of Cu-10%Gr-70%HS begins at j≤ 200 A/cm². The catastrophic wear mode of composite Cu-10%Gr-70% BS begins at higher current density values. Bearing steel exhibits the lowest wear intensity at j<200 A/cm².

The specific surface contact conductivity rᵢₛ =j/U (U is the contact voltage drop) grows at increase of j (figure 1,b). The contact conductivity achieves a maximum at some value of contact density j. The further increase in j leads to drop of rᵢₛ. The maximum of rᵢₛ value corresponds to the contact current density jₘ when catastrophic wear (figure 1,a) begins. It is noted that the bearing steel and also a composite on its base form the contact with higher conductivity of rᵢₛ in comparison with contacts of Hadfield steel and a composite on its base (figure 1,b). Contacts of cast bearing steel and cast Hadfield steel are characterized by higher values of conductivity rᵢₛ reached at the begin of catastrophic wear in comparison with that in contact of composites based on these steels (figure 1,b).

Sliding under current of high density leads to change of surface layer structure and to forming of tribolayer (figure 2). Thickness of tribolayer increases with increase of j and reaches the maximum value at the beginning of catastrophic wear. Tribolayer of bearing steel has the smallest thickness (a layer of white colour) and low quantity of flaw (figure 2,a, bottom photo). The BS based composite also forms rather thin tribolayer, but with a large number of flaw (figure 2,b, the bottom photo).
Figure 1. Current dependences of wear intensity $I_w$ (a) and of specific surface electric conductivity $r_s$ (b) of contacts of materials: 1 - cast bearing steel, 2 - cast Hadfield steel, 3 - composite Cu-10%Gr-70% BS, 4 - composite Cu-10%Gr-70% HS (Gr means the graphite).

Figure 2. Optical image of worn surfaces (the top photo) and of sliding surfaces cross-section (the bottom photo) of materials: a - cast bearing steel, b - cast Hadfield steel, c - composite Cu-10%Gr-70% BS, d - composite Cu-10%Gr-70% HS (Gr means the graphite).

Tribolayer of Hadfield steel has the high thickness and big quantity of flaw (figure 2, b, the bottom photo). The HS based composite also forms high tribolayer with a large number of flaw (figure 2, b, the bottom photo).

It should be noted that the sliding surfaces of bearing steel, of the composite on its base and of the Hadfield steel (figure 2,a-c, the top photos) contain the sectors with signs of material melting. Signs of obvious adhesion are not observed. One can see the formation of weak quasiliquid flow areas on the
sliding surface of composite of Cu-10%Gr-70%HS (figure 2,d, the top photo). But there are signs of adhesion. The melting of the sliding surface corresponds to a decrease in $I_h$. As a rule, high $r_s^{-1}$ corresponds to low $I_h$.

The difference in $I_h$ is due, in particular, to the phase composition of the tribolayer. X-ray diffraction researches showed that BS tribolayer and BS based composite tribolayer contain the phase $\alpha$-Fe and FeO (figure 3). X-ray diffraction pattern of HS tribolayer contain reflexes of the phases $\alpha$-Fe, $\gamma$-Fe and FeO after current collection sliding at catastrophic wear onset. The X-ray diffraction pattern of tribolayer of Cu-Gr-G13 composite contains only FCC phase reflexes. The lack of $\alpha$-Fe and of FeO on the sliding surface of composite of Cu-10%Gr-70%HS corresponds to its high wear intensity shown in figure 1.

![XRD diagrams of tribolayer structures of materials: 1 - cast bearing steel, 2 - cast Hadfield steel, 3 - composite Cu-10%Gr-70% BS, 4 - composite Cu-10%Gr-70% HS (Gr means the graphite)](image)

**Figure 3** XRD diagrams of tribolayer structures of materials: 1 - cast bearing steel, 2 - cast Hadfield steel, 3 - composite Cu-10%Gr-70% BS, 4 - composite Cu-10%Gr-70% HS (Gr means the graphite)

4. Discussion

Reduced $r_s^{-1}$ in the stage of catastrophic wear may be associated with saturation of surface layer by various structural defects, first of all, flaws (vacancy clusters, cracks, etc.). The low $r_s^{-1}$ of Hadfield steel and HS based composite contacts are due to their relatively high $\rho$ (table). Low $\lambda$ exert a strong influence on the manifestation of quite high $I_h$ (figure 1). High $I_h$ is observed at low FeO content in the present work. In the general case, low $\lambda$, high $\rho$ occur in metals with a complex primary structure (in intermetallic compounds, alloys having high content of chemical elements, etc.). It follows that high $I_h$ may be caused due to either low $\lambda$, or high $\rho$, or low FeO content on the sliding surface. Obviously, any combination of these factors will also lead to an increase in $I_h$. The presence of a low FeO content in the tribolayer should be recognized as the most strong factor for increasing of $I_h$ [1,4,6,7]. Therefore, the modification of SL due to the appearance of FeO oxide is necessary for reducing of $I_h$.

This is presented as one of the ways of expressing a general regularity, namely properties of a surface layer have more important meaning than properties of primary structure of material.

A tribolayer containing FeO and iron phases (figure 3) can be represented as a composite, where the iron phases serve as a metal matrix. The presence of solid solutions in a metal matrix causes a decrease in its ability to relax stresses by local plastic deformation in the vicinity of stress concentrators. It is obvious that stress concentrators occur in microvolumes adjacent to contact spots.
The stresses in these microvolumes relax easily if the metals in the tribolayer have high plasticity. Then the tribolayer is highly resistant to shear at the macroscale level and \( I_h \) has low values. Bearing steel and BS based composite have higher plasticity that promotes the best stress relaxation and localization of plastic deformation in thinner tribolayer. Relatively high heat conductivity (table) promotes appearance of low temperature gradients in contact zone and conformably low mechanical stresses in tribolayer. Quasiliquid state of a contact layer allows contact spots material to relax thermal and mechanical stresses by local plastic deformation easier and also to reduce the local shear stresses in contact. It provides high durability of the BS sliding surface.

Low thermal conductivity of high-alloyed Hadfield steel causes high temperature gradients on the sliding surface. This causes high mechanical stresses. But the solid solution of manganese in the primary structure of Hadfield steel reduces its plasticity. Therefore, the stresses relax weakly due to the transfer of plastic shifts to a relatively large depth. The low ability of HS based materials to relax stresses in a surface layer due to plastic deformation or its high ability to hardening leads to formation of tribolayer of higher thickness (figure 2, d, the bottom photo). A tribolayer with such low-ductile matrix has low strength and low shear resistance. This manifests itself as a high \( I_h \). Quasi-liquid state of the sliding surface arises as a result of plastic deformation of a thin surface layer. Low plasticity of the matrix in the HS based tribolayer makes it difficult to form a liquid. It can also be assumed that the presence of a high concentration of metal dissolved in the metal matrix prevents the formation of FeO or caused the decrease of the SL ability to hold FeO in the contact zone. One can assert that solid solutions of the metal in the metal primary structure lead to an increase in \( I_h \). Therefore it is probably that high entropy alloys will show low wear resistance under sliding current collection.

5. Summary
The impact of electric current on a contact surfaces of steels or steel based composites in dry sliding contact lead to tribolayer formation. The tribolayer thickness indicates the depth of deformation penetration. Low thickness of the bearing steel tribolayer and of composite on its base corresponds to higher wear resistance of these materials. Formation of FeO causes hardening of a sliding surface and facilitates a stress relaxation due to transition of a contact layer to quasiliquid state. It results in low wear intensity. Simpler primary structure of bearing steel and of composite on its base containing a small quantity of phases and the alloying elements, allows to reach higher wear resistance.

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