Relationship between the roughness of the friction surface of wear-resistant composites and their composition

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Abstract. The wear resistance of galvanic composites based on iron alloys under conditions of abrasive wear has been investigated. The relationship between wear resistance and surface roughness of composites during wear has been established. A model of the formation of the surface roughness of composites during abrasive wear is proposed. The optimal content of the dispersed phase in the composite was determined from the point of view of the ratio of the strength of the dispersed phase and matrix.

Keywords: composite materials, composite electrochemical coatings, electrolytic alloys, structure, mechanical properties, wear resistance.

1. Introduction

The high wear resistance of composite materials is associated with the fact that solid particles, protruding from a relatively soft matrix during wear, are the contact areas that are subjected to the most intense loading during friction. Possessing high physical and mechanical properties, they prevent adhesion of metal surfaces and seizure, and also contribute to better distribution of the lubricant over the working surface of the mating parts when it is insufficiently supplied to the mating. According to the classical theories of friction, wear of a composite is due to a combination of the properties of matrix materials and particles, their surface energy, structural features, and external conditions [1-3]. In the case of applying a distributed load, the stresses in the near-surface layer of the composite material are significantly lower than in the near-surface layer of solid inclusions [4].

Thus, the tribotechnical properties of “pure” metals and composites are closely related to the strength of the interacting dissimilar materials that make up the composition. At the same time, in a number of works, the formation of a favorable relief of the body surface by solid inclusions is put forward as the root cause [5]. To eliminate these disadvantages, studies were carried out, the purpose of which is to compare the strength properties of the composite components, the roughness of the wearing surface, the volumetric content and size of solid inclusions to determine their effect on the wear resistance of the material under abrasive wear conditions.

2. Research method

The physical and mechanical properties of the composites were studied using the example of galvanic composites based on iron alloys. Electroplating composites were obtained from electrolytes based on ferric chloride. To study the effect of the strength properties of the matrix on wear resistance, galvanic composites based on iron-nickel and iron-cobalt were selected, the mechanical properties of which were studied in detail earlier [6, 7]. Electrocorundum micropowders of grades M14, M20 were used as a solid filler.

A detailed technology for producing galvanic composites is given in [6, 7]. Studies of abrasive wear resistance were carried out in accordance with GOST 23.208-79 on a specially designed installation [6]. The test time was determined by the need to obtain a tangible amount of wear (J, mg), which was determined by the gravimetric method with an error of 5 10⁻⁸ kg. The profilogram of the outer part of the surface of the rough layer of composites was obtained on a «MarSurf PS1» device.

Traditionally, to determine the quality of the surface layer of composites, the results of structural analysis are used [8, 9], a similar approach was used to assess the characteristics of galvanic composites.
Experimental data were processed by methods of mathematical statistics. To construct functional dependencies, regression analysis was used [10, 11].

3. Results and discussion

Figure 1 shows the galvanic composites obtained of high quality, dense, with a uniformly distributed dispersed phase.

When studying the abrasive wear resistance of composites, it was found that their wear in contact with a non-rigidly fixed abrasive largely depends on the size and volume content of dispersed particles in the coating (V), both at the stage of running-in and during steady-state wear. The wear of composites based on iron-nickel and iron-cobalt alloys decreased with increasing filler content and passed through a minimum at a micropowder content of the order of 18–25% (vol.). With an increase in the filler content in the material to 30–35% (vol.), the wear resistance of the composites decreased. It should be noted that galvanic composites with a stronger matrix had the highest wear resistance. Thus, the optimal wear resistance of composites based on iron-cobalt (filler content 22–26% (vol.)) was higher than composites based on iron-nickel (18–20% (vol.)).

![Figure 1. The structure of composites based on an iron-nickel alloy with the inclusion of white electrocorundum (x400): M10 (a); M20 (b)](image)

Figure 2(a), shows the investigation of the surface roughness of composite material specimens established in the process of testing which shows that with an increase in the volumetric content of the filler in the galvanic composite from 0 to 5–7% (vol.), the roughness slightly increased. With a further increase in the filler content in galvanic composites to 18–25% (vol.), the roughness decreased to $Ra = 0.5–0.7 \, \mu m$, reaching a minimum when the content of filler particles in the composite corresponds to the highest wear resistance of the material. It is quite characteristic that less strong and softer galvanic composites based on iron-nickel had a higher roughness than composites based on iron-cobalt.

Analyzing the nature of changes in the surface roughness of composite materials after research, it can be noted that when testing composites with a minimum filler content, the roughness of their surface in contact with the abrasive is formed by the structural features and elastoplastic properties of the matrix material. Moreover, the surface of iron-cobalt coatings (more durable) is formed somewhat rougher than iron-nickel ones.

Figure 3(a) shows the model of such a surface can be depicted as a set of spheres. With an increase in the content of particles in the composite to 5–7% (vol.), figure 3(b) shows the roughness of the matrix material is gradually replaced by the roughness of solid inclusions. There is a high hardness in comparison with the matrix of the composite, during wear they protrude from the surface much higher and are subjected to more intense loading. In this regard, due to the limited strength of the bond and their connection with the matrix, chipping of individual filler particles occurs (Fig. 3, b). Galvanic composites based on iron-nickel (less strong) retained filler particles worse and, accordingly, their surface was formed coarser than that of galvanic composites based on iron-cobalt (more durable) (see Fig. 2).
Figure 2. Relationship between the wear (a) and roughness (b) of galvanic composites on the content and size of the filler: 1 – Fe-Ni-Al₂O₃ M14; 2 – Fe-Ni-Al₂O₃ M20; 3 – Fe-Co-Al₂O₃ M14; 4 – Fe-Co-Al₂O₃ M20

Figure 3. Model of a rough surface of a material without a filler (a), composites with a content of filler particles below optimal (b), optimal (c), and above optimal (d).

Figure 3(c) shows a further increase in the content of particles in composites to 15–22% (vol.) led to a more complete replacement of matrix irregularities by “irregularities” from solid filler particles. The interaction of the roughness of the solid phase increased, respectively, the wear resistance of the material increased, and the roughness decreased to a minimum corresponding to the optimal content of filler particles (see Fig. 2 and 3, c). With an increase in the filler content in the composites above the optimum, the ability of the matrix to retain solid particles decreased. Figure 3(d) shows that during wear, they began to crumble and break down, which led to a sharp increase in the surface roughness of the composites.

It should be noted that the surface of the most wear-resistant composites, regardless of the properties of the matrix material, with an optimal filler content, has almost the same roughness established during their wear. The change in the surface roughness of galvanic composites during their wear and the relationship between their wear resistance and the properties of the matrix and the bond strength of the filler particles with the matrix is especially clearly revealed when plotting the dependences of the roughness on their wear. Figure 4 shows a decrease in the surface roughness of the samples with decreasing wear to a minimum value, and then its growth after exceeding the optimal filler concentration in the composite, can be represented by second-order regression equations obtained on the basis of statistical processing of experimental data:

at a section $AB$

$$Ra = -0.021J^2 + 0.352J - 0.433;$$

(1)

at a section $BC$

$$Ra = -0.011J^2 + 0.619J - 1.470;$$

(2)

at a section $AD$
Ra = -0.029J^2 + 0.446J - 0.413; (3)

at a section DE

Ra = -0.149J^2 + 1.989J - 3.755; (4)

at a section FG

Ra = -0.062J^2 + 0.961J - 2.417; (5)

at a section GH

Ra = -0.028J^2 + 0.492J - 0.707; (6)

at a section FK

Ra = -0.021J^2 + 0.302J - 0.118; (7)

at a section KL

Ra = 0.092J^2 - 0.503J + 1.192. (8)

Comparison of the wear resistance and roughness of the composites showed that the more wear-resistant galvanic composites had a lower roughness. This confirms the conclusions of the work of S.N. Einbinder that in the process of wear, an equilibrium roughness of the composition is established on the friction surface, which depends on their elastoplastic properties and wear conditions [5].

Figure 4. Relationship between the steady-state surface roughness on the wear of composites based on Fe-Ni (a) and Fe-Co (b): 1 – Fe-Ni-Al2O3 M14; 2 – Fe-Ni-Al2O3 M20; 3 – Fe-Co-Al2O3 M14; 4 – Fe-Co-Al2O3 M20

Analysis of relationships (1) - (8) showed that the optimal content of filler in the most wear-resistant composites can be accurately determined by calculation, as the point of intersection of the branches of the dependences of roughness on wear, respectively, up to and after the optimal content of filler particles. Thus, the study of the relationship between the roughness of composite materials and wear can serve as a method for determining the optimal content of solid filler in composite materials that correspond to their highest wear resistance under abrasive wear conditions.

By comparing the curves of the dependence of the surface roughness of the samples on wear, it is possible to clearly identify the relationship between wear resistance and the strength properties of composites. Since wear is associated with surface destruction, the best wear resistance should correspond to the highest strength of the material. A theoretical analysis of the relationship between the strength of the compositions and their wear resistance showed that their optimum for CEC meets the condition [15]:

\[ \sigma_c = \sigma_r, \]

where \( \sigma_c \) and \( \sigma_r \) are the strength of the composite and the DC strength (when the composition breaks, the crack passes through the binder and DC particles).

In this case, the volumetric content corresponding to the highest strength of the composite \( V_p \) during its destruction:

\[ V_p = 0.33 \pi (1/\alpha_p^2 \cdot \gamma_p/\gamma_m + 0.816)^2, \]

where \( \alpha_p \) is a coefficient that depends on the type of packing of DC particles in a heterogeneous material; \( \gamma_p, \gamma_m \) are the surface energy of the material of the DC particles and the matrix, respectively.
Thus, increasing the strength of the matrix and the bonding of the filler with the matrix is an important factor in increasing the wear resistance of composite materials. In the process of obtaining galvanic composites, the strength of the matrix can be increased by alloying electrolytic iron with nickel or cobalt. Electrodeposited alloys, in comparison with “pure” electrolytic iron, have higher elastoplastic properties, wear resistance and adhesion strength to the base, and lower internal stresses [7, 12, 15]. The chemical bonds of the phases in the composite material can be increased by heat treatment of the surfaces of the parts. During heat treatment, the elastoplastic properties of the matrix of galvanic composites are improved due to a decrease in microdistortions of the crystal lattice and the decomposition and release of chemically adsorbed compounds and their products from materials from the sediment [13, 14].

4. Conclusion

Relationships between wear resistance and surface roughness of composites during wear are obtained. A model of the formation of the roughness of the friction surface of composites during abrasive wear is proposed. The basic relationships between the structure and elastoplastic properties of composite materials under conditions of abrasive wear have been established. The wear resistance of composites can be improved by increasing the strength of the matrix material and the strength of its bond with the filler during electrolysis or heat treatment of parts. Moreover, the last condition is more preferable in connection with the simplification of the technology of obtaining galvanic composites and the technological advantage of thermal treatment of coatings with high frequency current and laser.

References

[1] Kragelsky I V 1984 Friction units of machines: Handbook Moscow: Mashinostroenie 280 p
[2] Rybakova L M 1982 Structure and wear resistance of metal M.: Mashinostroenie 212 p
[3] Nelyub V A 2018 Adhesive-Strength Evaluation via the Pull-Out Method in a Binder—Elementary-Filament System at Various Treatments of Filaments Polymer Science – Series D 11(3) pp 263-266
[4] Kisel Y E, Serpik I N, Markaryants L M, Bezik V A, Guryanov G V, Bezik D A 2015 Calculation of the elastic Characteristics of Composite Materials with Dispersed Inclusions. International Journal of Applied Engineering Research 10(24) pp 44018-44022
[5] Ainbinder S B 1981 Roughness parameters of the counterbody that determine the wear resistance of polyethylene Friction and wear 2(1) pp 12-21
[6] Kisel Yu E 2001 Increasing the durability of wear parts of agricultural machinery with composite electrochemical coatings based on iron alloys: abstract of Ph.D. dis. Cand. tech. sciences. M. 18 p
[7] Kisel J E, Guryanov G V 2018 Wear Resistance of Composite Coatings Based on Iron Alloys IOP Conf. Ser.: Mater. Sci. Eng. 450 032047
[8] Nelyub V A 2016 A study of the microstructure of dress glass fibers Polymer Science – Series D 9(1) pp 96-100
[9] Nelyub V A, Berlin A A 2013 A study of the chemical structure of the surface of carbon fibers before and after oxide Polymer Science – Series D 8(3) pp 175-180
[10] Kolemaev V A 1991 Probability theory and mathematical statistics M.: Higher school 400 p
[11] Brom A E, Stoyanova M V, Yazev M V, Korolev S A 2020 Assessment of technological resources for the production of composite products based on mathematical methods IOP Conf. Ser.: Mater. Sci. Eng. 934 012003
[12] Shaidulin A M 1990 Increasing the adhesion strength of electrolytic iron with alloy steel when restoring parts of agricultural machinery: author. dis. ... Cand. tech. sciences. Kishinev 19 p
[13] Guryanov G V 1985 Electrodeposition of Wear Resistant Compositions Kishinev: Shhtiintsa 237 p
[14] Guryanov G V 1989 Structure and mechanical properties of electrolytic iron coatings Kishinev: IPF 62 p
[15] Kisel Yu E 2014 Improving the durability of agricultural machinery parts by electrothermal treatment of composite electrochemical coatings: dis. Dr. Tech. sciences. Bryansk 249 p