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Optimal structure of wear-resistant compositional materials

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Abstract. The heterogeneous structure of composites is linked to their wear resistance under abrasive wear conditions. It was found that the DP content in the CEC corresponding to the highest strength of the wear-resistant material depends on the ratio of the strength properties of the matrix and the filler. It can be calculated using the continuum theory for the case of two-sided congestion of elliptical dislocations.

1. Introduction

Aim of the work was identify the influence of heterogeneous structure of compositional materials for its wear-resistant in abrasive wear conduction. They due high wear-resistant of compositional materials, combines solid disperse phase with relatively “soft” elastic matrix, with the fact that parts of filler protruding in the process of wear out from the matrix, are those contact areas which, are subjected to the most intense loading under the friction. The stresses in the near-surface layer of the composite matrix are significantly lower than in the near-surface layer of solid inclusions, since the external uniformly distributed load, uniformly deforming the different-module components, causes corresponding stresses in them.

Typical representatives of such composites are composite electrochemical covering based on iron, chromium, nickel and other metals. These composites are widely distributed and can serve as a convenient model for studying the strength properties of materials.

The functional purpose of the dispersed phase in the composite is to absorb the load and evenly distribute it in the binder. Due to the filler, the relief of the friction surface, which ensures better preservation of the lubricating membrane is formed, and surface of grasp is prevented. The high strength and hardness of the particles of the dispersed phase prevents wear of the most stressed protruding sections of the micro relief of the working surface of the part, providing maximum resistance to plastic deformation (with scratching, cutting, compression and crushing, which occur in friction).

2. Basic Theoretical Provisions

The interrelation among the structure, strength and wear resistance of composite coatings is based on the relationships that determine the strength of composite materials for shift in accordance with discrete and continual dislocation theories, the equations of the connection of normal and tangential stresses, and the equations for calculating the strength of filler particles for rupture and separation [1-6]. Causes of destruction of composites can be: cracking of the matrix; cracking of particles, since the strength and structure of the particles depend on their size; violation of adhesion bonds between phases on surface of section [6].

Strength of particles and matrix material in accordance with the Griffiths-Orovana ratio can be determined as

$$\sigma_p^2 = \frac{8\gamma_p G_p}{(1-\mu_p)d}, \tag{1}$$

$$\sigma_m^2 = \frac{8\gamma_m G_m}{(1-\mu_m)l}, \tag{2}$$

where γ_p and γ_m - unit energy of destruction of particles and matrix, respectively; G_p and G_m are the shear modulus of the particle and the matrix, respectively; d is the equivalent particle diameter; l is the average distance between the particles; μ_p and μ_m - Poisson's ratio of the particle and the matrix, respectively.

Parts of filler is more strength then matrix and delay its destroy preventing the spread of cracks. As part of discrete and continual theory average shear stress τ at one-sided cluster of dislocation according to work [5,6] is:

$$\tau = \frac{Gb}{\pi(1-\mu)d}, \tag{3}$$

Where G and μ are the shear modulus and Poisson's ratioof material, respectively; b – Burgess' vector.
For two-sided cluster of dislocation according the work [12] is:

$$\tau = \frac{Gb}{(1-\mu)d}. \tag{4}$$

The most size of non-destructed particle may be set from equality of theoretical strength of particles for rupture and strength on Griffiths-Orovana depend on the size:

$$\sigma_p = \alpha_p \tau_p, \tag{5}$$

Where α_p is coefficient depended from type of laying of particles of dispersed phase (DP) in composite electrochemical coating (CEC); τ_p shear stress in ДФ. Substitute expression (5) in (3) taking into account that in the brittle destroy theoretical meaning:

$$\gamma_p = G_p b_p / C_p, \tag{6}$$

Where G_p and b_p are shear modulus and the Burgers vector of the DP; C_p - constant, depending on the properties of the DP material, the greatest strength of particles is:

$$\sigma_p = \alpha_p\ G_p / C_p, \tag{7}$$

according to the discrete theory, for crack growth within a single grain ($d_{рд}$) and for the continuum theory for elliptical ($d^э_{рк}$) and cylindrical ($d^ц_{рк}$) forms of cracks:

$$d_{рд} = (2/\alpha^2_p)\ b_p C_p/(1-\mu); \tag{8}$$

$$d^э_{рк} = (4/\alpha^2_p)\ b_p C_p/(1-\mu); \tag{9}$$

$$d^ц_{рд} = (8/\pi\alpha^2_p)\ b_p C_p/(1-\mu). \tag{10}$$

The minimum distance between particles corresponding to the highest strength of the composite is determined from the theoretical shear strength of the composite ($\tau_к$) and DP particles (τ_p):

$$\tau_к = \tau_р \,. \tag{11}$$

Substituting the values of the quantities for the discrete theory, we obtain the critical distance between the particles ($\lambda_д$):

$$\lambda_д=1/(1-\mu)\ (G_м b_м\ C_р)/(\pi\ G_р). \tag{12}$$

Using the transformation of $\gamma_м = G_м b_м / C_м$ and $C_м \approx C_р$ - for the matrix (12) expression will take the following form:

$$\lambda_д=1/(1-\mu)\ (\gamma_м/\gamma_р)\ b_р\ C_м/\pi. \tag{13}$$

For the continuum theory of strength, the expression for the distribution of the critical distance between particles ($\lambda_к$) is:

$$\lambda_к=1/(1-\mu)\ (\gamma_м/\gamma_р)\ b_р\ C_р. \tag{14}$$

The coefficient of stress concentration in the DP ($K_р$) can be determined from the ratio:

$$K_р=\sigma_р/\sigma_к=\beta\lambda/d, \tag{15}$$

Where $\beta = d_i/\lambda_i$, where d_i and λ_i - are largest size of nondestructive particles and the critical distance between particles, respectively.

The ratio of the highest strength of the dispersed phase and the composition by conditions (11) must be equal to 1. Indeed, in the ideal case, the highest strength of the composite can be equal to the theoretical strength of the particles. Therefore the ratio $\sigma_р/\sigma_к=1$ will be right, than coefficient of stress concentration in DP will be

$$K_р=(\lambda/d)\ (d_i/\lambda_i)=(d_i/\lambda_i)\left(\sqrt{\pi/3V_{дф}}-\sqrt{2/3}\right). \tag{16}$$

Taking into account expression (16), we define the Kp of composite through the physical parameters of the phase components and the volume content of the DP in CEC:

- for a discrete theory:

$$K_{рд}=(2\pi/\alpha^2)(\gamma_р/\gamma_м)\left(\sqrt{\pi/3V_{дф}}-\sqrt{2/3}\right); \tag{17}$$

- for the continuum theory: when elliptical cracks or loops of dislocations pass through the composite:

$$K^э_{рк}=(2\pi/\alpha^2)(\gamma_р/\gamma_м)\left(\sqrt{\pi/3V_{дф}}-\sqrt{2/3}\right), \tag{18}$$

and when cylindrical cracks passing through:

$$K^ч_{рк}=(8/\alpha^2)(\gamma_р/\gamma_м)\left(\sqrt{\pi/3V_{дф}}-\sqrt{2/3}\right). \tag{19}$$

Coefficient of stress factor in matrix of composition K_M can be calculated using the known rule of mixtures:

$$K_м=(1-V_{дф}\ K_р)/(1-V_{дф}). \tag{20}$$

Analysis of obtained ratio shows that there must be observed bending, depending on the volume content of the DP on dependence curves of stress concentration from volume content of particles in CEC.

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Let's perform the calculation of the DP content in the CEC, which corresponds to the highest strength of the composite upon its destruction, when the crack passes through the matrix and dispersed particles. The condition for such destruction will be the following ratio

$$\sigma_p/\sigma_к = K_p = \beta\lambda_к/d_к \text{ или } \sigma^2_p/\sigma^2_к = K^2_p = (\beta\lambda_к/d_к)^2. \quad (21)$$

Since the calculation must be carried out for all cases of destruction, let us consider its principles in one of the variants, for example, when applied to studying of a composite strength of the discrete theory of dislocations and the passage of cracks within a single grain. The ratio $\sigma_p/\sigma_к$ for such a case will be equal to:

$$\sigma^2_p/\sigma^2_к = \frac{\dfrac{2\gamma_p G_p}{(1-\mu)d_к}}{\alpha_p^2 \dfrac{G_м b_м G_p}{\pi(1-\mu)\lambda C_p}} = \frac{2\pi}{\alpha_p^2}\frac{\lambda}{d_p}\frac{\gamma_p}{\gamma_м}. \quad (22)$$

It follows from (22) that:

$$\sigma^2_p/\sigma^2_к = 4\lambda_к/(\pi d_к)^2 = \frac{2\pi}{\alpha_p^2}\frac{\lambda}{d_p}\frac{\gamma_p}{\gamma_м}. \quad (23)$$

Expression (23) allows us to determine the ratio λ/d for the sought case in the form:

$$\frac{\lambda}{d_p} = \frac{\pi^3}{8\alpha_p^2}\frac{\gamma_p}{\gamma_м}. \quad (24)$$

Taking into account the dependence of the volume content of DP in the CEC from the ratio [6]:

$$\frac{\lambda}{d_p} = \alpha\sqrt{\frac{\pi}{3V_{дф}}} - \sqrt{\frac{2}{3}}, \quad (25)$$

it is possible to obtain an expression relating it to the strength properties of the CEC components:

$$\frac{\lambda}{d_p} = \frac{\pi^3}{8\alpha_p^2}\frac{\gamma_p}{\gamma_м} = \sqrt{\frac{\pi}{3V_{дф}}} - \sqrt{\frac{2}{3}}. \quad (26)$$

From expression (26) we obtain the volume content of the DP corresponding to the highest strength of the CEC in the framework of the discrete theory:

$$V^{д}{}_{дф} = \frac{\pi}{3}\frac{1}{\left(\dfrac{\pi^3}{8\alpha_p^2}\dfrac{\gamma_p}{\gamma_м} + \sqrt{\dfrac{2}{3}}\right)^2}, \quad (27)$$

In a similar way, we obtain a relation for the passage of cracks through polycrystals in the framework of the continuum theory:

$$V^{к}{}_{дф} = \frac{\pi}{3}\frac{1}{\left(\dfrac{\pi^3}{\alpha_p^2}\dfrac{\gamma_p}{\gamma_м} + \sqrt{\dfrac{2}{3}}\right)^2}. \quad (28)$$

Considering the continuum theory for cases of two-sided accumulation of dislocations for cases of elliptic and cylindrical cracks, we obtain, respectively:

$$V^{кэ}{}_{дф} = \frac{\pi}{3} \frac{1}{(\frac{1}{\alpha_p^2} \frac{\gamma_p}{\gamma_м} + \sqrt{\frac{2}{3}})^2}, \tag{29}$$

$$V^{кц}{}_{дф} = \frac{\pi}{3} \frac{1}{(\frac{8}{\alpha_p^2} \frac{\gamma_p}{\gamma_м} + \sqrt{\frac{2}{3}})^2} . \tag{30}$$

The aforecited ratios is imply the existence of ideal bond between the DF and the matrix at level of highest strength of the composition (for example, for electrolytic iron $\gamma_м^{ж}$ = 2000 erg/cm^2; cuprum $\gamma_м^{м}$ = 1200 erg / cm^2, nickel $\gamma_м^{н}$ = 1700 erg / cm^2; alundum γ_p = 3600 erg / cm^2 [1-5]). Its real value can be in the range $0 \leq \sigma_{р\text{-}м} \leq \sigma_p$, that can be taken into account by varying the quantities $\gamma_p/\gamma_м$ in the ratios (29) - (31).

The verification of the obtained theoretical ratio, using the example of CEC of iron-alundum, nickel-alundum, and cuprum-alundum [1-5] showed that calculation results based on the continuum theory, when cracks are modeled as two-sided congestions of elliptical-form dislocations, are the closest to the actual ones. The results of calculating the volume content corresponding to the highest strength of the coatings according to (29) and the experimental studies are in good agreement (Fig. 1), if we take into account the presence of boundary conditions for theoretical studies [5].

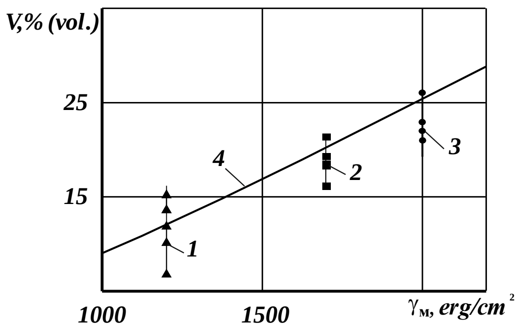


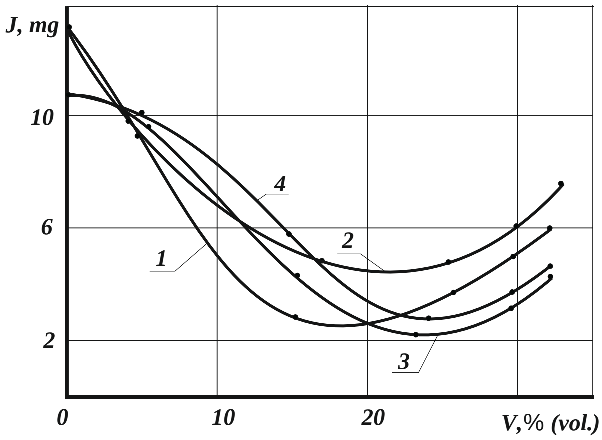
Figure 1. Influence of matrix strength on the optimal volume content of electrocorundum particles in CEC based on: 1 - cuprum; 2 - nickel; 3 - iron; 4 - by the expression (29).

3. Results of experimental research

The object of the study was samples with composite coatings based on iron alloys with inclusion of white corundum filler (makes M14, M20).Iron-nickel (as less durable) and iron-cobalt (as more durable) coatings, whose mechanical properties have been studied previously, were chosen for study the effect of strength properties of the matrix on the composites wear-resistance [1,5]. A detailed technology of the obtaining of composite coatings is described in [5]. Studies of abrasive wear-resistance were carried out in accordance with GOST 23.208. The experimental data were processed by methods of mathematical statistics [1].

Thus, the wear-resistance of the CEC with increasing of matrix strength and strength of bond the DP and matrix should increase when cobalt, nickel and other elements are introduced into electrolytic iron. Precipitated alloys in comparison with the "pure" electrolytic iron have higher elastic-plasticity properties, wear-resistance and strength of adhesion to the basis, lower internal stresses [1-5]. The content of solid DP in wear-resistant CEC based on iron should be 24 ... 28% (vol.).

If increasing of DP content in the coating more than 30% (vol.), wear-resistance of the CEC decreased. It should be noted that the CEC with a stronger matrix had the highest wear-resistance. Thus, the optimal wear resistance of CEC based on iron-cobalt coatings (DF content 24 ... 26% (vol.)) was higher than the CEC based on iron-nickel coatings (DF content 18 ... 22% (vol.)).



1 – Fe-Ni-Al_2O_3 (M14); 2 – Fe-Ni-Al_2O_3 (M20); 3 – Fe-Co-Al_2O_3 (M14); 4 – Fe-Co-Al_2O_3 (M20)

Figure 2. Dependence of the wear of the CEC from the content (*V,%* (vol.)) and the dimensions of DP in the coating.

4. Conclusions

The heterogeneous structure of composites is linked to their wear resistance under abrasive wear conditions. It was found that the DP content in the CEC corresponding to the highest strength of the wear-resistant material depends on the ratio of the strength properties of the matrix and the filler. It can be calculated using the continuum theory for the case of two-sided congestion of elliptical dislocations.

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