Technology of applying antifriction coatings using an electric arc pulsating power

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Abstract. The coating of a mechanical mixture of metal powders and solid lubricant material is due to difficulties due to the low adhesive and cohesive strength of the resulting coatings. This problem can be avoided when using in the process of the pulsating power electric arc (PPEA). The object of research in the paper is an anti-friction coating based on ПГ-ХН80СР3 powder with the addition of 20% by volume of graphite ПГ-50, of which plasma coating using PPEA gave a coating with friction coefficients \( f_{\text{тр min}} = 0.038 \) and \( f_{\text{тр max}} = 0.062 \) under contact load of 300 MPa. The test results of a friction pair, carried out for 500 hours on a path of friction of 55,000 m, showed the stability of the friction coefficient within \( f_{\text{тр}} = 0.056 \ldots 0.061 \). The application of the coating process using the surface activation of the PPEA allowed us to obtain high-strength anti-friction coatings with the content of a solid lubricant element in the coating composition up to 20% of the total coating volume.

Keywords. Antifriction coatings, plasma spraying, pulsating power electric arc (PPEA), graphite, clad materials.

1. Introduction

The process of applying coatings from a mechanical mixture of metal powders and a solid lubricant material is associated with certain difficulties. Such fine solid lubricants, such as graphite, molybdenite, boron nitride, copper fluoro-cyanide, etc., envelop the metal particles and prevent their solid connection between themselves in the coating composition and with the surface of the part.

The content of powder solid lubricant usually does not exceed 3-8% of the volume of the coating material. With a higher content of solid lubricant powder in the coating volume, its adhesion and cohesive strength sharply decrease, up to shedding the coating when it contains 12-15% solid lubricant. However, only at 15-30% of the content of solid lubricants unique anti-friction properties of solid lubricants appear [1-4].

Excellent material for creating antifriction coatings - graphite, has the ability at a temperature exceeding 10,000 K in an oxidizing atmosphere to interact with such materials as: nickel, cobalt, molybdenum, silicon, boron, titanium, niobium, or most carbides [5].

As carbon dissolves to form carbide compounds, the solubility of the elements decreases and some of the unbound graphite remains, firmly combined with materials [3].

Due to the high activation energy (\( E_a = 7.5 \text{ eV} \)), chemical interaction of metals with graphite, with the formation of a sufficiently strong compound, can occur only in areas with the highest energy, causing thermal fluctuation of chemical bonds. The temperature of interaction of materials such as Ni, Cr, B, Ti with graphite is 1200-16000K [6].

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2. Materials and methods

ΠГ-ХН80СР3 powder was taken as the initial composition of the antifriction coating with dispersibility (63-80)·10^-6 m. In the coating 20% by volume of graphite ΠГ-50 was introduced with dispersibility (40-63)·10^-6 m.

The heating temperature of the coating at the local points of attachment of the PPEA and the contact time of the phases were limited by the condition of the formation of a minimum thickness of the Ni – Ti intermetallic compound layer. The adopted maximum heating temperature is Tmax = 13,000 K.

The contact time of the phases determines the formation of a durable metallurgical compound of materials in the event that they have time to go through the processes of developing physical contact between the liquid and solid phases of materials and the chemical interaction of the phases. The duration of the contact phase tk is determined by the following equation (1):

\[ tk = t_p + t_d + t_{oa} + t_{pc} \]  

where: \( t_p \), \( t_d \), \( t_{oa} \), \( t_{pc} \) – respectively, the time of interphase surface energy retardation (the delay time of diffuse transitions); the time of development of heterodiffusion processes to the formation of supersaturated solid solutions; the time required for the formation of new chemical compounds; time of further growth of chemical compounds.

By limiting the contact time \( t_k \) to only the first two terms of equation (1), the condition of joining materials is satisfied. The boundary of the molten volume of the coating material, as shown by metallographic studies, is a spherical surface with a center in the spot of the binding of an electric arc on the surface [7].

The thickness of the coating \( h \) is much less than the thickness of the part \( H \) (\( h \ll H \)). In this case, the entire thermophysics of the cooling process is determined by the material of the part.

![Figure 1. Melt bath cooling model](image)

Since the molten bath of the coating material is a finite volume (Figure 1) bordering on a cold metal, we use the model of cooling a rod of finite length, the more so that the thermal conductivity of air \( \lambda_{\text{возд}} \) is much less than the thermal conductivity of metal parts \( \lambda_0 \) (\( \lambda_{\text{возд}} \ll \lambda_0 \)) and the losses to the surrounding the atmosphere can be neglected [8]. In this case, the heat distribution is isotropic; thermal processes in the coating can be neglected and the thermophysical parameters of the coating material at the melting point can be taken.
Thus, the task becomes one-dimensional, and on the basis of [5], we write the heat equation in the form (2):

$$\frac{c \rho}{\lambda} \frac{dT}{dt} = \frac{dT^2}{dx^2}$$

(2)

where: \(c, \rho, \lambda\) are the specific heat capacity, density, and thermal conductivity, respectively.

The initial and boundary conditions are determined by the following equations (3-6):

$$T|_{t=0} = T(X)$$

(3)

$$T|_{x=0} = T_{\text{max}}$$

(4)

$$T|_{x=L} = T_w$$

(5)

$$T|_{x=H} = 0$$

(6)

The final solution of equation (1) is presented in the form (7):

$$T(x,t) = T_{\text{max}} \cos \frac{\pi d}{6r} \exp \left( \frac{D^2 \pi^2 \lambda}{36r^2 c \rho} \right) t$$

(7)

From the obtained expression (7), it is possible to estimate the contact time \(t_c\) of the phases of the material, provided that at the center of the molten coating volume (\(x = 0\)) the temperature \((T(0, t_c) = T_{\text{melt}})\) of melting is reached during cooling. From here we get the equation (8):

$$t_c = -\frac{36\pi^2 h^2 c \rho}{\pi^2 D^2 \lambda} \ln \frac{T_{\text{melt}}}{T_{\text{max}}}$$

(8)

The formation of a strong phase connection and the alternation of melted inclusions in a certain order given by the speed of movement of the plasma torch relative to the part and the frequency of current pulses of the PPEA contributes to the formation of a coating possessing the properties of a composite material.

Substituting in the expression (8) the values of thermophysical constants for the Ni material, the coating thickness is \(5 \cdot 10^{-4}\) m (applied in one pass of the plasma torch), the value of the coefficient \(D = 0.2\), we find that the contact time is \(t_c = 10^{-2}\) s.

The power of the pulse PPEA is calculated by the formula (9):

$$N = \frac{9.7T_w \lambda h^2}{\sqrt{\pi \alpha \left[ 0.56 \exp \left(-R/\sqrt{\pi \alpha} \right)^2 - R/\left(2\sqrt{\pi \alpha} \right)(1-\text{erf}\left(R/2\sqrt{\pi \alpha}\right)) \right]}$$

(9)

and is \(N = 600\) W at a frequency of 100 Hz. This value of power is allocated in PPEA at a current of \(I = 30\) A at a distance from the substrate to the plasma torch nozzle section \((42-44) \cdot 10^{-3}\) m. The relative velocity of the plasma torch in this case was taken equal to \(v = 10^{-2}\) m/s [9, 10].

3. Results and discussion

The structure of the ПГ-ХН80СР3-50 graphite is shown in Figure 2. The coating contains large inclusions of free graphite in a dense nickel matrix containing phases CrC, BC, SiC, hardness 192.4-212.8 MPa and a small number of nitrides.

The diffuse transition region from the coating to the titanium alloy was \((2-3) \cdot 10^{-5}\) m, and the hardness of the transition zone is 131.4-152.4 MPa. The structure of the titanium alloy BT14-16 below the diffuse...
transition zone did not change as compared with the exemplary structure, which confirms the conclusion about the allowable impact on the sample. The hardness of the titanium alloy was 36.7-44.7 MPa.

Figure 2. The microstructure of the coating ПГ-ХН80СР3 with 20% graphite applied using PPEA

The coating test was carried out at a contact load of 300 MPa on a MACT-1 friction machine. The following values of the friction coefficients are recorded: $f_{\text{тр min}} = 0.038$ and $f_{\text{тр max}} = 0.062$.

For comparison, a coating applied by the method of traditional plasma spraying without the use of PPEA was tested. A coating containing up to 10% by volume of graphite when loaded with an indenter on a MACT-1 friction machine to a load of 0.17 MPa, was completely destroyed.

Figure 3. Coating microstructure Ni(C) + 20%Co (x 200)
From the analysis of the friction coefficient variation curves depending on time or on the friction path, selected for further testing of friction pair, in which the antifriction coating is Ni (C) + 20% Co material and the counter surface is Al2O3 + 50% ZrO2 ceramics. The microstructure of the Ni (C) + 20% Co coating deposited using PPEA is shown in Figure 3.

The test results of this pair of friction, carried out for 500 h on the path of friction 55,000 m, showed the stability of the coefficient of friction within \( f_{\text{frp}} = 0.056-0.061 \). The wear of samples of a friction pair was determined on a profilogram — a model 362 profilometer and amounted to \( \delta = 1.6 \cdot 10^{-6} \) m for an antifriction coating. At the same time ceramic coating wear is not detected. The microstructure and characteristic macrostructure of the surface of the coating Ni (C) + 10% Co, applied using PPEA are shown in Figures 4 and 5.

**Figure 4.** The microstructure of the coating Ni (C) + 10% Co, deposited using PPEA (x 200)

**Figure 5.** Characteristic surface macrostructure Ni (C) + 10% Co, applied using PPEA
The results of the analysis of the conducted studies show that the inclusions of graphite are fixed in the composition of the coating by dense metallic formations of Ni and Co. At the same time ceramic coating wear is not detected.

4. Conclusions.
1. Theoretical prerequisites for the application of high-strength antifriction coatings with a friction coefficient \( f = 0.038–0.062 \) were created.
2. The application of the coating process using the surface activation of the PPEA allowed us to obtain high-strength anti-friction coatings with the content of a solid lubricant element in the coating composition up to 20% of the total volume.

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