Structure and properties of Cr–Al–Si–B coatings produced by pulsed electrospark deposition on a nickel alloy

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ABSTRACT

This study investigates the kinetics of pulsed electrospark deposition (PED) on a heat resistant Ni-alloy substrate with Cr–Al–Si–B electrodes of three compositions. The optimal deposition frequency and energy mode (E = 0.048 J, I = 120 A, f = 3200 Hz, τ = 20 μs) were established. This mode is characterized by the minimum electrode erosion at a satisfactory coating deposition velocity. Studies were conducted on the structure, phase composition and coating properties. It was shown that the electrospark coating deposition using Cr–Al–Si–B electrodes significantly increased the hardness, heat resistance and wear resistance of the nickel alloy EP718-ID (similar Inconel 718). The application of the PED process and electrodes could be recommended to protect the surfaces of functional parts and units constructed of Ni alloys.

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1. Introduction

In many respects, the development of the aircraft industry influences the machine-building industry and has a significant impact on the economy. The aviation engine technology is an expensive sector of the engineering industry concerning materials and components, energy intensity and the complexity of technological operations [1], so the development of the new high-quality materials and coatings is a priority direction of the science and technology.

To increase the service life of Ni alloy parts for critical applications, protective coatings applied using various surface engineering methods are widely used [2]. The most effective protection against oxidation at high temperatures is the addition of elements to the alloy composition that form thermodynamically stable oxide compounds. Chromium, aluminium and silicon are the most commonly used elements for this application, and they contribute to the formation of a protective layer on iron–carbon, Ni and other alloys. These elements oxidize at high temperatures in the open air faster than an alloyed metal and form a complete protective oxide coating [2].

One of the promising methods of surface treatment is pulsed electrospark deposition (PED) [3–13], which is used to prevent the

oxidation of Ni alloys [14,15]. The advantages of PED coatings are high adhesion, the possibility of local surface treatment, the inclusion of large-sized products, the relative simplicity of implementation, the absence of strict requirements for surface preparation prior to application, and a high reliability of equipment [3,16,17]. The technological process of coating deposition is ecologically safe, and it is characterized by low power consumption, high profitability and rapid return on investment. Metals, graphite, and hard alloys based on tungsten carbide of VC and TC grades are used as electrode materials. However, coatings fabricated with these electrode materials do not provide: the high level of heat resistance for Ni alloys used under extreme conditions.

Earlier, hard alloy electrode materials based on titanium, tantalum, chromium carbides, titanium diboride [18], as well as the heat resisting cobalt-based KhTN-61 [19] were proposed. These electrodes were produced through the self-propagating high-temperature synthesis (SHS) technology [18], which made it possible to simplify the industrial process of the electrode production and reduce the ballast content. Nevertheless, the coatings made from these electrodes don't provide the necessary level of wear resistance at high temperatures. That's why the development of new compositions for the electrodes that would contain hard and oxide-generating components in order to obtain scale- and wear resistant coatings with enhanced functional properties is an important and relevant task. The work proposes to try out electrode materials based on chromium boride and chromium aluminide

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(Cr–Al–Si–B system) as possible candidates for further enhancing the performance specifications of the nickel alloy EP718-ID.

The work was aimed at studying the peculiarities of electrospark coatings formation, their compositions, structures and properties on substrates made from the refractory nickel alloy EP718-ID with using Cr–Al–Si–B system electrode materials.

2. Materials and methods of research

In this study, we used Cr–Al–Si–B alloys as electrode (anode) materials. These materials were produced by self-propagating high-temperature synthesis (SHS) [20]. Table 1 shows the chemical and phase composition of the selected electrode materials.

We employed the commonly used EP718-ID (similar foreign alloy Inconel 718) heat resistant Ni alloy as a substrate (cathode). This alloy is widely applied to engine technology. The alloy composition is C ≤ 0.1; Cr ~ 14.0 ÷ 16.0; Ni ~ 43.0 ÷ 47.0; Fe ~ 22.0 ÷ 33.0; Mo ~ 4.0 ÷ 5.2; W ~ 2.5 ÷ 3.2; Nb ~ 0.8 ÷ 1.5; Ti ~ 1.9 ÷ 2.4; Al ~ 0.9 ÷ 1.4; Mn ~ 0.60; Si ~ 0.30; Zr ~ 0.02; Ce ~ 0.10; B ~ 0.008; S ~ 0.010; P ~ 0.015.

The size of the samples for investigation was $10 \times 10 \times 5$ mm, and the area of the surface treated was 1 cm^2. The size of the samples for tribological tests was 21×21 mm.

The PED coatings were deposited using an Alier-Metal 2002 commercial electrical discharge unit. The vibration frequency of the electrode-anode was 600 Hz. The applied frequency and energy modes of electrospark treatment are described in Table 2.

Depositions were performed in the open air. All of the areas of the treated surface were subjected to the alternate local action of a pulsed discharge by repeatedly passing the anode over the same portion of the cathode.

The kinetics of mass transfer (the erosion of anode material Δa and the cathode weight increment Δk) was measured gravimetrically on KERN 770 analytical scales with a maximum error of 10^{-5} g after each minute of alloying.

The total cathode weight increment ΣΔk [3,16] was determined from the following formula:

$$\sum \Delta k = (\Delta k_1 + \Delta k_2 + \dots + \Delta k_{10})/\rho \tag{1}$$

where Δk_i is the cathode weight increment per i-minute of alloying, g;

i = 1, 2…10, min; and

ρ is the density of the electrode material, g/cm^3.

The total anode erosion ΣΔa was calculated by analogy.

The polished specimens were prepared on a Struers Roto Pol-21 automatic grinder polisher. The microstructure was examined using a Neophot-32 optical microscope and a Hitachi S-3400 N scanning electron microscope equipped with a NORAN energy-dispersive X-ray spectrometer. Microhardness was measured with a PMT-3 M instrument at a 20-g load in accordance with GOST 9450-76. X-ray diffraction (XRD) measurements for the coatings were obtained on a DRON-4 automatic diffractometer using monochromatic CuKα radiation in step-by-step scanning mode in the 2θ range of 10 ÷ 110° with the scan increment of 0.1° [21].

Heat resistance tests were carried out in an SNOL 7.2/1200 electric furnace at 700 °C and with a 40-h exposure. The oxidation

Table 2
Energy modes of the PED process.

Mode	Voltage (U), V	Current peak value (I), A	Pulse duration (τ), μs	Energy of a single pulsed discharge (E), J	Frequency (f), Hz
1	20	120	20	0.048	3200
2	20	120	40	0.096	1600
3	20	120	80	0.192	800

* – $\sum E = E \times f \times 60$ s.

weight gain (K_{weight}), which is a change in the mass of the sample due to oxidation per unit surface, was determined using the following formula:

$$K_{weight} = (m_1 - m_0)/S_0 \tag{2}$$

where: m_0 is the initial weight of the sample, g;
m_1 is the weight of the sample after oxidation, g; and
S_0 is the area of the sample surface, m^2.

The tribological properties of the coatings were determined in accordance with international standards ASTMG 99-959 and DIN 50324 on a High-temperature Tribometer company "CSM Instruments" operating in the pin-on-disc mode. A ball of Al$_2$O$_3$ (6 mm in diameter) was used as the counter pair. Coated samples were allowed to slide at a linear velocity of 10 cm/s under a load of 1 N. The temperature of the experiment was 500 °C. The dependency of the friction pair friction coefficient on the path length of the counter pair (300 m) was defined by a computer using InstrumX software.

The profile of the wear track and roughness of the coatings (the arithmetic mean roughness value R_a) was evaluated using a Veeco WYKO NT1100 optical profilometer.

The wear rate was calculated using the following formula:

$$W = (s \times L)/(N \times 1) \tag{3}$$

where W is the wear rate, mm$^3 \cdot$N$^{-1} \cdot$m^{-1};
L is the perimeter of circle, mm;
s is the sectional area of the wear groove, mm^2;
N is the load, N; and
l is the sliding distance, m.

The composition of the wear products was analysed by infrared spectroscopy using a Vertex 70v vacuum-path Fourier spectrometer (Bruker), according to the frustrated total internal reflection technique. Vacuum was used as the background. All of the spectra were processed after the baseline correction. The spectra were measured in the spectral range of 400 to 4,000 cm^{-1}. The resolution was 4 cm^{-1}.

3. Research results and discussion

In PED practice, to obtain data on the electrode material, dependencies of the total anode erosion ΣΔa and the total cathode weight increment ΣΔk on the treatment time are determined. These dependences can help to define the intensity of the electrode material transfer on a part and thickness of the formed coating. Indirectly, these dependencies provide an idea of the dynamics of growth of a coating. Based on these dependencies, frequency-energetic parameters of the electrospark

Table 1
Chemical and phase composition and properties of electrode materials.

Electrode material	Cr, %	Al, %	Si, %	B, %	Phase composition, %	ρ, g/cm^3	P, % %
Composition 1	69.4	8.1	12.0	10.5	65% CrB + 27% Cr(Si,Al)$_2$ + 8% Cr$_5$Si$_3$B$_x$	5.3	13.2
Composition 2	65.8	16.2	12.0	6.0	35% CrB + 26% Cr$_5$Si$_3$ + 39% Cr$_4$Al$_{11}$	4.9	8.2
Composition 3	63.4	21.6	12.0	3.0	15% CrB + 24% Cr$_5$Si$_3$ + 57% Cr$_4$Al$_{11}$ + 4% Cr$_5$Si$_3$B$_x$	4.7	2.1