Досліджена структура покриттів, отриманих плазмовим методом на середньовуглецевих сталях. Покриття отримували з композиційного матеріалу, що містить зносостійку складову $SiC–Al_2O_3$ і металеву зв'язку на основі заліза. Металева зв'язка була отримана в результаті розмелу композиції в сталевих барабанах. Вивчені триботехнічні характеристики отриманих покриттів в умовах тертя без змащувальних матеріалів в умовах підвищених температур. Визначені особливості і закономірності механізмів їх зношування в умовах підвищених температур

Ключові слова: композиційне покриття, адгезія, плазмове напилення, зносостійкість при підвищених температурах, зміцнення, електронна мікроскопія

Исследована структура покрытий, полученных плазменным методом на среднеуглеродистых сталях. Покрытия получали из композиционного материала, содержащего износостойкую составляющую $SiC–Al_2O_3$ и металлическую связку на основе железа. Металлическая связка была полученная в результате размола композиции в стальных барабанах Изучены триботехнические характеристики полученных покрытий в условиях трения без смазочных материалов в условиях повышенных температур. Определены особенности и закономерности механизмов их изнашивания в условиях повышенных температур

Ключевые слова: композиционное покрытие, адгезия, плазменное напыление, износостойкость при повышенных температурах, упрочнение, электронная микроскопия

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ANALYSIS OF STRUCTURE AND TRIBOTECHNICAL PROPERTIES OF PLASMA CARBIDE-SILICON COATINGS UNDER CONDITIONS OF ELEVATED TEMPERATURES

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1. Introduction

As it is known, temperature is a controlled but not manageable factor of a tribological system. At present, only the most general laws of heat exchange in a tribosystem have been determined. On the basis of the structural-energy theory of friction and wear [1], the summary work of friction is consumed directly in the process of wear of surface layers and for a change in internal energy of the elements of a tribosystem (triboelements and environment). An imposition of external heating on this complex process may essentially influence the energy balance of a tribosystem and, as a result, its wear resistance.

At present, a technology of coatings is admitted to be the most effective method of the surface protection, and components and technology of their application have a tendency toward a reduction in cost, energy and resource consumption and in the equipment complexity [2–5]. Therefore, this research is devoted to the study of mechanisms of structure formation, wear resistance and mechanisms of coatings wear under conditions of elevated temperatures of the contact zone. We selected the system of carbide silicon-aluminum oxide with the metallic phase based on iron as the components for the coating. Plasma spraying was selected for the coatings application. The studied coatings may be used for the protection of components of ground-based aviation equipment subjected to triboinfluence under conditions of elevated temperatures.

Development of coatings with the high performance properties is a relevant task of aircraft construction, machine building and vehicle operation. In this case, coatings must be composed of inexpensive and available components, for the production of which there are sufficient raw materials in the resource base of Ukraine.

2. Literature review and problem statement

Carbide-silicon coatings have been of interest for many researchers from the very beginning of basic research into silicon carbide [2] as a rather effective measure for protecting the surface of machine parts from wear, corrosion and thermal influence. The selected initial components of coating, together with the reasonable cost, have certain shortcomings for the application of carbide– silicon coatings: the activity of silicon carbide, recrystallization grain growth, porosity and adhesion to the surface – all these led researchers to studying new physical and physical-chemical phenomena, which make it possible to avoid these negative phenomena. Thus, for instance, interaction with metallic melts, used for metallic bonds, made it necessary to use alloys with passivating additives and sometimes intermetallic compounds instead of pure metals. At the same time, low specific weight of silicon carbide in comparison with metals (by 2 times) led to the stratification of charge into heavier and lighter constituents and the sedimentation of the latter sharply decreased. Increased porosity of carbide-silicon coatings requires the application of inert components with enhanced plasticity for the increase in continuity of coatings.

Thus, in paper [3], carbide-silicon coatings were applied by the plasma method to aluminum pistons of internal combustion engines to increase their heat and wear resistance and efficiency due to a decrease in heat withdrawal of the mixture to an aluminum piston. For this purpose, the coating was applied by the air-plasma method, layer by layer, with the combined upper layer. Besides heat and wear resistance, a positive influence on the specific fuel consumption and the emission of engine was also shown. In article [4], the researchers demonstrated satisfactory tribotechnical properties of the composite on the basis of silicon carbide in the matrix from metallic aluminum. In this case, the intensity of wear varied from $3–6\cdot 10^{-8}$ $mm^3/N\cdot m$. In study [6], the coatings were applied by the same method using aluminum oxide, and a positive influence of existence in such coatings of iron based compounds, in particular oxides, was shown. The hardness of the obtained coating is 1.98 MPa. In paper [7], it was shown that with the thermal treatment of the composite on the basis of silicon carbide in the metallic matrix its resistance to abrasive wear increases dramatically. In article [8], researchers showed high sensitivity of applied coatings from non-deficit carbides and oxides to the application method under conditions of serial and mass production.

Compact ceramics based on $SiC–Al_2O_3$ system was studied earlier and demonstrated a high level of tribotechnical properties, alongside with it, a number of technological measures for obtaining high– dense and finely dispersed heterogeneous systems in the form of compact materials were explored. This research was followed by a number of studies into the possibility of applying this ceramics as protective wear-resistant coating, which resulted in solving a number of optimization problems on the composition and using different procedures for the purpose of obtaining wear resistance equal to that of the compact material. Thus, an attempt to introduce the metallic bond, used both independently and together with the refractory component, was made, and in this case different gas-thermal methods of coating application were used. In article [9], it was established that the coatings, obtained by detonation method, have very low adhesion to the steel surface due to a very low content of phases based on iron and their adhesive destruction occurs at the load of 5 MPa. In paper [10], the coatings from this composition, applied by the plasma method, were studied and tested without being heated. There is a scientific interest in testing such coatings under conditions of controlled heating, for which an additional technological measure was used, namely, applying intermediate sublayer to avoid flaking of ceramic coating under conditions of thermo-cycling and establishing the temperature limit of wear resistance of these coatings. It is necessary to emphasize that there is no any scientifically substantiated and practically implemented solution at present to the problem of applying carbide-silicon coatings for the protection from wear resistance of parts that work under conditions of elevated temperatures.

3. The aim and tasks of the study

The aim of present study is to obtain coatings with enhanced wear resistance under conditions of elevated temperatures.

To achieve the set aim, the following tasks were formulated:

– obtaining wear-resistant coatings from the $(SiC–Al_2O_3)–FeSi$ system by the plasma spray method with the sublayer from Ni_3Al;

– testing these coatings for wear resistance under conditions of elevated temperatures;

– determining the mechanisms of wear of the obtained coatings under conditions of elevated temperatures.

4. Materials and procedure of testing

4. 1. Preparation of charge for coating

The powders of aluminum oxide (TU 6-09-2486-77), the average dimensions of which was 40–45 µm, and of silicon carbide with the average dimensions of 45–50 µm of the 64C make (GOST 26 327-84) in concentration of 50 % of SiC and 50 % of Al_2O_3 were mixed for grinding and homogeneous mixing. Mixing was performed in steel drums with steel grinding bodies in the planetary mill "Sand-1" in acetone medium for 32 hours.

The obtained charge was dried and sifted through the sieve. The amount of milling yield of iron, which comprised 19.3 % by weight, was determined by the methods of chemical analysis. The obtained charge was pressed at temperature of 1540 °C for conglomerating the components of ceramics with metallic bond, then the charge was ground and sifted to the particle dimensions from 63 to 130 µm.

4. 2. Application of coating and study of the structure

The coatings were applied in the plasma plant "OPU-3D" (Ukraine), at which the optimum modes of application of plasma coatings were determined by thickness and continuity of coating. The following modes were defined for the obtained composition. The plasma-forming gas was the mixture of $Ar+H_2$. The transportation gas was Ar. Argon consumption comprised 45 l/min. The distance of spraying was 130 mm.

Current strength of the plasma-forming burner was 500 A. Voltage between the electrodes was 65 V. The coating was applied to the plate for the analysis of adhesion, residual stresses and metallographic examinations with the thickness of 100 µm. With the application of the coating on the end surfaces of cylindrical samples for the friction testing machine "plane-plane" with the heating element, the thickness was 200 µm. For the purpose of testing the coatings for wear resistance at the controlled heating, the Ni_3Al interlayer was applied by the same plasma method from the powder PN85U15 (TU 14-1-3282-81) with granularity of 100–140 µm. The thickness of the sublayer from nickel aluminide varied from 50 to 70 µm.

The structure of plasma coatings from the composite material $(SiC–Al_2O_3)–FeSi$ was explored by the method of electron microscopy in the raster electron microscope REM-106I and in the diffraction X-ray phase analyzer DRON-3.0.

4. 3. Tribotechnical tests of the obtained coating and studying of friction surfaces

The composite plasma coating from the ($SiC-Al_2O_3$)–$-FeSi$ system was tested in the friction testing machine by the scheme "plane-plane" together with the steel counterbody without any lubricants, with the controlled heating at temperatures ranging from 200–500 °C in the range of slip rates of 2–7 m/s and of loads of 2–6 MPa. A schematic of the friction node of the plant is shown in Fig. 1. The load was applied to shaft 1 of the vertical drilling press 2A135. The friction speed was determined by the conversion of rotation frequency into linear speed. In this case, two cylindrical samples 3 with the coating, applied at the end surface, were set in the chuck. Friction was attained on the steel counterbody 5, where in the proximity of the friction path, thermocouple 6 was installed for controlling temperature in the friction zone. Temperature in the friction zone was elevated with the aid of heating element 4, which was an annular Ni-chrome spiral, packed inside housing 2, turned from a fireproof composition.

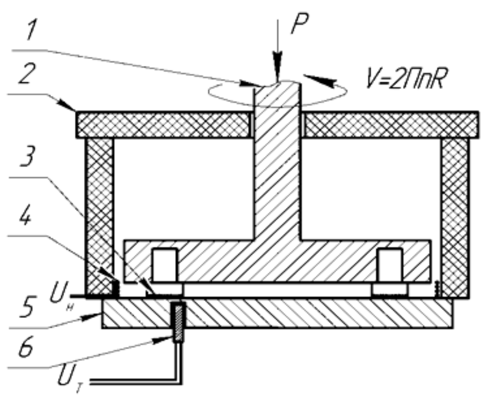


Fig. 1. Schematic of friction node of plant with heating: 1 – shaft of machine; 2 – heatproof housing; 3 – sample with coating; 4 – heating element; 5 – counterbody; 6 – thermocouple

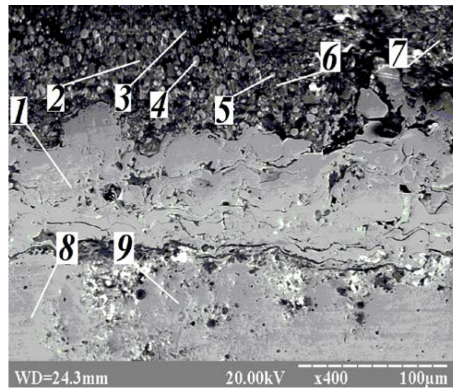
The friction surfaces of the samples with coating were studied in the raster electron microscope REM-106I (Ukraine) and in the diffraction X-ray phase analyzer DRON-3.0 (USSR).

5. Results of studying the structure and heat and wear resistance of carbide-silicon coatings

5. 1. Results of study

The general morphology of coating is represented in Fig. 2 in three photographs: in reflected (Fig. 2, *a*), in secondary (Fig. 2, *b*) and in topographic study of the surface (Fig. 2, *c*). Results of micro X-ray spectral analysis of the points, indicated in Fig. 2, are presented in Table 1.

From the first photograph, it is possible to draw the conclusion that the coating is a two-layered system with thickness of ~200 μm. The interlayer from the base (spectra 8–9, Fig. 2, *a*) is a lamellar structure of nickel aluminide Ni_3Al (spectrum 1, Fig. 2, *a*) with thickness of about ~70 μm. The external layer of coating is a heterophase system, which consists of three characteristic phases and a sublayer closely fitted to the buckled surface. The first type of phases is the particles of silicon carbide (spectra 2–3, Fig. 2, *a*), evenly distributed in the volume of the coating. The second type of phases include the phases (spectra 4–5, Fig. 2, *a*) based on iron and silicon (about 20 %) of a drop-like shape with fused edges in the plasma jet.



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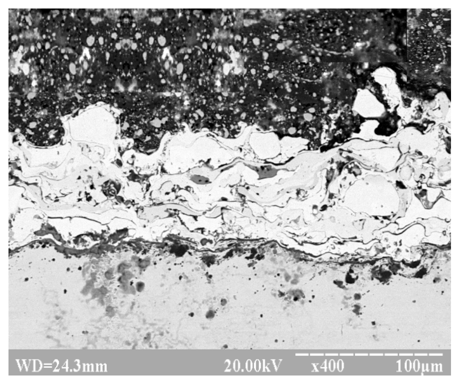

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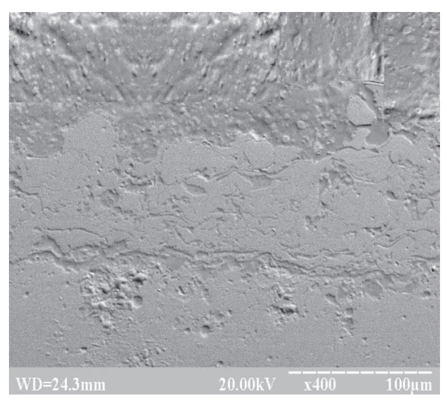

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Fig. 2. Microstructure of the obtained plasma coatings of the (SiC–50 % Al_2O_3)–$FeSi$ system with the sublayer: *a* – in reflected; *b* – in secondary; *c* – surface topography with the indication of sections of micro X-ray spectral analysis at. % in Table 1

The third type of phases is aluminum oxide of the matrix type (spectra 6–7, Fig. 2, *a*), having the matrix morphology of the surrounding phase of the first and second types. The adhesion of this coating was tested by the pin method and comprised 20 MPa, the type of detachment from the steel base layer is adhesive. In the secondary electrons (Fig. 2, *b*), the phases, which have metallic structure (in the coating about 25–30 %), are highlighted in the image with white colour, since they possess higher conductivity and are the most intensive source of secondary electrons. The topographic study of the cross section surface (Fig. 2, *c*) of the coating gives the idea about porosity of the coating, which comprises larger than 15 %. It should be noted that the structure of plasma coating is very similar to that of detonation coating from the same composition [9]. However, in this study it was established that the coating has unsatisfactory adhesion to the base layer and is completely flaked in the process of tribointeraction at the load as low as 5 MPa; therefore, the interlayer from aluminide of nickel was used. The assumption about the stoichiometric relationship of phases in the coating was proved by the X-ray phase analysis of the surface of coating, which revealed SiC, Al_2O_3, $Fe_{1,34}Si_{0,66}$, Fe_3Si, Fe in the coating of the phase. The dimensions of ceramic inclusions vary from 4 to 7 μm.

Table 1

Results of micro X-ray spectral analysis of the points indicated in Fig. 2, *a**

Spectra	C	O	Al	Si	Fe	Ni
Spectrum 1	0.00	0.00	13.85	0.00	0.00	86.14
Spectrum 2	49.14	0.00	0.00	50.88	0.00	0.00
Spectrum 3	44.18	0.00	0.00	55.81	0.00	0.00
Spectrum 4	0.00	0.00	0.00	23.51	76.48	0.00
Spectrum 5	0.00	0.00	0.00	21.99	77.99	0.00
Spectrum 6	0.00	53.15	46.65	0.00	0.00	0.00
Spectrum 7	0.00	54.99	44.99	0.00	0.00	0.00
Spectrum 8	0.02	0.00	0.00	0.00	99.96	0.00
Spectrum 9	0.01	0.00	0.00	0.00	99.97	0.00

*Note: * – the values are given in at. %*

Since the developed coating is the means of wear protection under conditions of elevated temperatures, the plasma carbide-silicon coatings of the $(SiC–Al_2O_3)–FeSi$ system were tested to wear resistance under conditions without heating and under conditions of elevated temperatures. This makes it possible to determine applicability conditions for the new obtained coatings by the load-speed and temperature modes. Tribotechnical tests were conducted according to two schemes:

– the influence of friction speed was studied at the constant load of 4 MPa;

– the loading effect on the intensity of wear and friction coefficients, respectively, were studied at the constant speed of 7 m/s.

In this case, three temperature modes were used: without heating, 250 °C and 500 °C.

Results of tribotechnical tests of the composite plasma coatings at the constant load showed that, with an increase in speed, the intensity of wear decreases from 60.2 μm/km at the testing speed of 2 m/s to 34.89 μm/km at the testing speed of 7 m/s without heating the contact friction zone (Fig. 2, *a*, curve 1). At heating the contact friction zone to 250 °C, with an increase in speed in the same range, the wear decreases from the value of 141.13 μm/km to 53.57 μm/km (Fig. 2, *a*, curve 2). But at the further increase in temperature of the contact friction zone to 500 °C for the same values of friction speed, a decrease in the values of wear of coatings from 90.0 μm/km to 50.84 μm/km was observed (Fig. 2, *a*, curve 3).

Depending on friction speed, friction coefficients in the process of coating testing vary in the limits from 0.43 to 0.41 without heating the contact friction zone (Fig. 2, *b*, curve 1). Further heating of the contact friction zone to 250 °C indicates frictional mode of coating friction, and friction coefficients amount to 0.44–0.52. But further heating of the friction contact zone to 500 °C shows the transition of the friction of coatings into antifrictional mode 0.31–0.32.

Testing the samples with the coatings at a constant speed of 7 m/s showed (Fig. 2, *c*) that with a load increase, the wear intensity increases at R=2 MPa and at R=6 MPa for all the studied temperature modes. In particular, the wear intensity without heating with a load increase grows from 30.1 μm/km to 40.16 μm/km (Fig. 2, *c*, curve 1). At heating the friction contact zone to 250 °C, the wear intensity increases in the range from 9.40 to 51.84 μm/km (Fig. 2, *c*, curve 2). This range changes insignificantly in case of heating the friction contact zone to 500 °C and amounts to 16.13 to 53.57 μm/km (Fig. 2, *c*, curve 3).

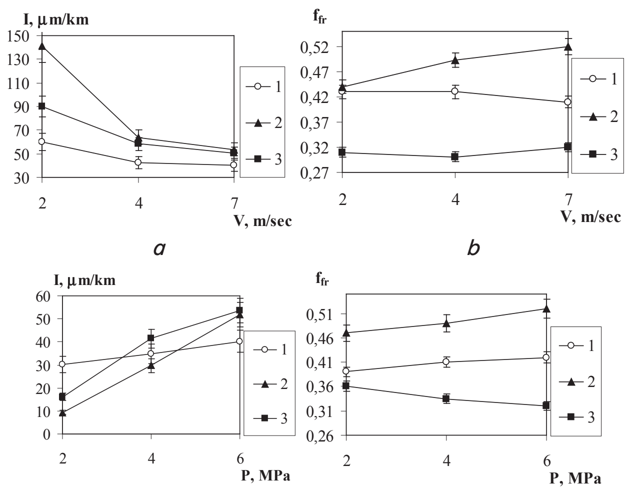


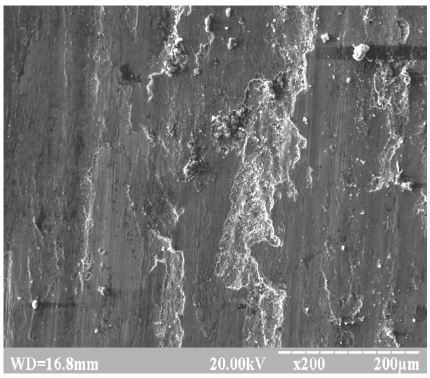
Fig. 3. Dependence of wear intensity and friction coefficient of plasma coating of the $(SiC-Al_2O_3)$-FeSi system: *a, b* — on speed; *c, d* — on load; at different temperatures: 1 — without heating; 2 — 250 °C; 3 — 500 °C

Friction coefficients of plasma coating increased with the load increase from 2 to 6 MPa (Fig. 2, *d*) and showed the same nature of changing as the increase in temperature of the friction contact zone of coating. Thus, without heating, friction coefficients changed from 0.39 to 0.42 (Fig. 2, *d*, curve 1). At heating to 250 °C, the coating worked as frictional in the range of 0.47–0.52 (Fig. 2, *d*, curve 2). At further heating of the friction zone to 500 °C, the coating worked as antifrictional again and friction coefficients comprised 0.36–0.32 and decreased with a load increase (Fig. 2, *d*, curve 3). Thus, the developed coating behaves differently in different temperature ranges. The wear intensity of the steel counterbody in the process of testing did not exceed 15–30 μm/km.

5. 2. Discussion of obtained results

To explain the results received and to establish the mechanisms of friction and wear of the obtained coatings, the friction surfaces of samples with the coating, obtained under extreme conditions the coating friction (V=7 m/s, R=6 MPa) and at a temperature of 250 °C and 500 °C were studied in the electron microscope REM-106I. The studies were conducted in the reflected, secondary electrons and in topographic mapping at magnification 200 and 400 (Fig. 4–7).

The structure of the friction surface of composite coatings, tested at the temperature of 250 °C at magnification 200 is shown in Fig. 4. The general morphology of this friction surface is shown in Fig. 4, *a*, in the secondary electrons.



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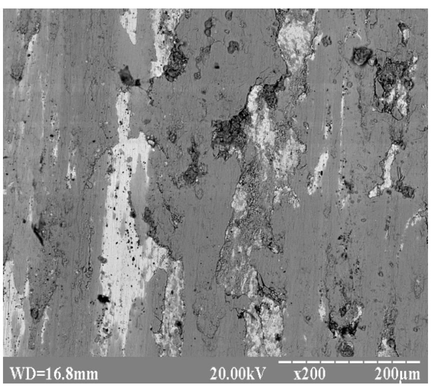

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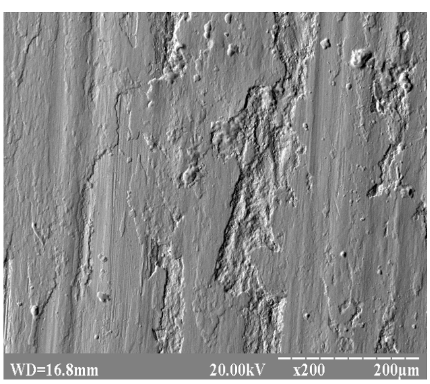

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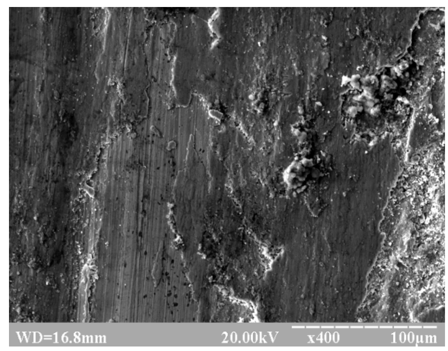
Fig. 4. Friction surfaces of coating of the ($SiC-Al_2O_3$)-FeSi system at magnification 200 with a temperature of 250 °C: *a* – in reflected electrons; *b* – in secondary electrons; *c* – surface topography

At magnification 200, it is possible to establish that at a temperature of 250 °C the heterogeneous coating system gets amorphized and converted into a homogeneous film. It is evenly distributed around the area of the real contact and is flaked from the surface in the form of wear products in places of the increased contact pressure. In the process of studying this friction surface in reflected electrons (Fig. 4, *b*), it is possible to draw the conclusion that the film is inhomogeneous and has sections with more pronounced metallic properties. Thus, the islet sections of a lighter phase contrast are observed at the surface. Studying the surface topography (Fig. 4, *c*), it is possible to arrive at the conclusion that an amorphous film of the gray phase contrast is located in the contact plane, and more metal-like islets are located considerably lower than the contact surface. For more distinct studying of the nature and the composition of the surface films, this friction surface was explored at magnification 400 and a micro X-ray structural analysis of the most characteristic friction sections was carried out. Results of this study are presented in Fig. 5. Results of a micro X-ray spectral analysis of the points, indicated in Fig. 5, *b*, are presented in Table 2.



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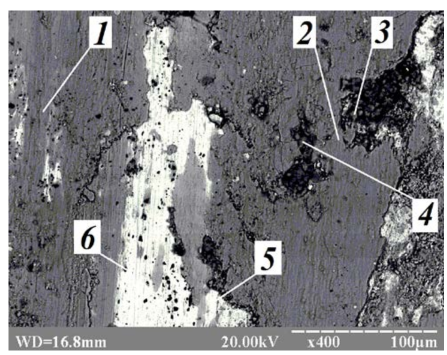

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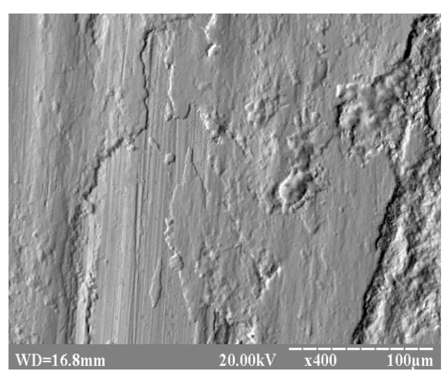

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Fig. 5. Microstructure ×400 of the section of friction surface of coating at 250 °C: *a* – in reflected; *b* – in secondary; *c* – surface topography with the indication of sections of micro X-ray spectral analysis at. % in Table 2

Table 2

Results of micro X-ray spectral analysis of points, indicated in Fig. 5, *b**

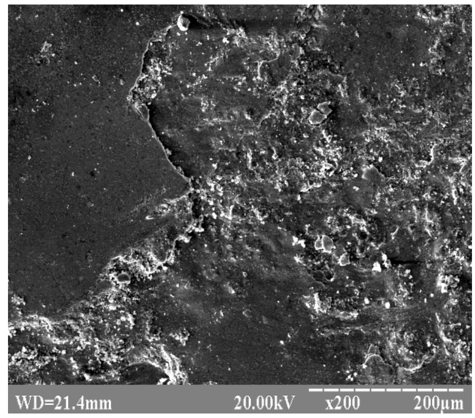
Spectra	C	O	Al	Si	Fe	Ni
Spectrum 1	0.00	48.09	18.75	20.01	13.15	0.00
Spectrum 2	0.00	49.08	19.16	19.98	11.76	0.00
Spectrum 3	49.14	0.00	0.00	50.88	0.00	0.00
Spectrum 4	44.18	0.00	0.00	55.81	0.00	0.00
Spectrum 5	0.00	0.00	10.73	00.00	2.14	87.11
Spectrum 6	0.00	00.00	15.38	0.00	0.19	84.40

*Note: * – values are given in at. %*

It is a two-phase system, which consists of two sections (Fig. 5, *a–c*). As a result of a micro X-ray spectral analysis of the sections, indicated in Fig. 5, *b*, it was established that they contain aluminum, silicon and iron in combination with sufficiently high concentration of oxygen up to 49 % (spectra 1 and 2, Fig. 5, *b*). Apparently, this amorphous film consists of complex compounds of oxides of the spindle type. It was proved by the X-ray phase analysis of the friction surface, which determined clear reflections of oxides Al_2O_3, SiO_2, Fe_2O_3. Moreover, in separate places of crumbling, separate inclusions of silicon carbide are clearly registered (spectra 3 and 4, Fig. 5, *b*). As far as light metal-like sections are concerned, it is possible to establish that this is the interlayer from nickel aluminide Ni_3Al with iron traces up to 2 % (spectra 5 and 6, Fig. 5, *b*). A topographic analysis of this surface shows that it is the amorphous film from the three–component system of oxides that is in tribotechnical contact. It should be noted that the intensity of coating wear under conditions at a temperature of 250 °C comprises 53.57 μm/km and friction coefficient is 0.52.

The friction surfaces of the indicated coating at a temperature of 500 °C at magnification 200 in the reflected, secondary electrons, as well as the surface topography are shown in Fig. 6. Thus, from the obtained electronic photographs, it is possible to establish that the friction surfaces get covered with films of entirely different nature than in the case of heating this coating to temperatures of 250 °C, shown in Fig. 4, 5. It is originally noticeable that these surface films possess the enhanced hardness, since they do not have any slip lines unlike the surfaces, shown in Fig. 4, 5. The wear products of these friction surfaces are, apparently, the continuous cleavages of the friction surfaces. Studying the general morphology of the friction surface of the coating both in reflected electrons (Fig. 6, *a*) and in secondary electrons (Fig. 6, *b*), it is possible to draw the conclusion that the structure of both the surface layers of the friction films and the deep layers are absolutely similar. This allows drawing the conclusion that heating of coating up to 500 °C leads to the complete structural transformation of coating throughout its entire thickness, but not to adhesive flaking of this coating, which is undoubtedly a positive effect of the preliminarily applied sublayer from the intermetallic compound Ni_3Al.

Fig. 6, *c*, shows topography of the friction surface of the coating at temperature 500 °C. From the Figure, it is possible to draw a conclusion that in contrast to 250 °C (Fig. 4, *c*), the friction surface of the coating on the left (Fig. 6, *c*) absolutely does not have slip lines, which indicates high hardness of this intermediate phase, in comparison with the surface of the steel counterbody at this temperature. It should be noted that the absolutely smooth section of the friction surface of this coating substantially decreases its contact pressure, but simultaneously with this, it can substantially increase possible adhesive interaction of the friction surfaces.



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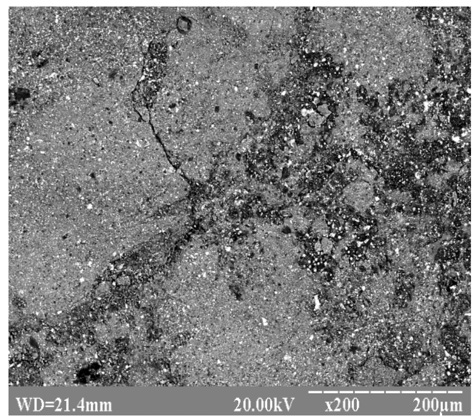

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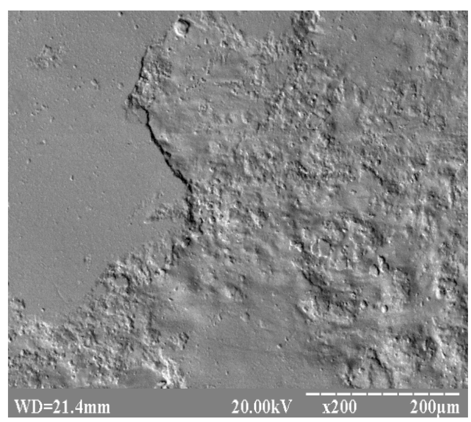
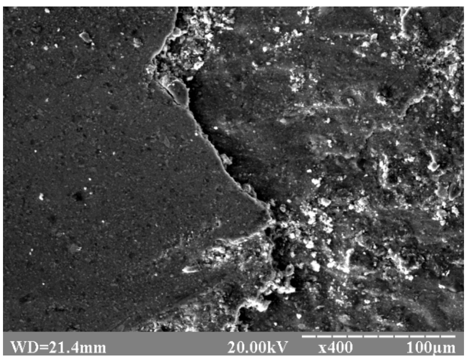


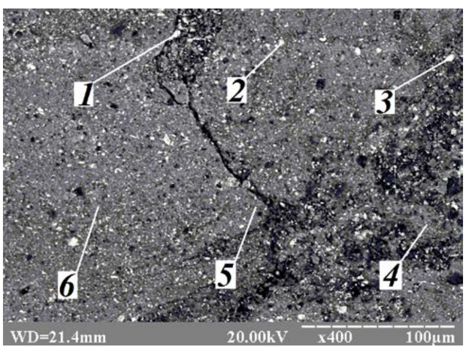
c

Fig. 6. Friction surfaces of coating of the ($SiC—Al_2O_3$)—FeSi system at magnification 200 at temperature 500 °C: *a* — in reflected electrons; *b* — in secondary electrons; *c* — surface topography

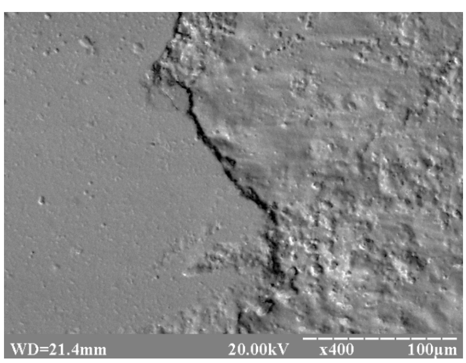
For more detailed studying the friction surface of this coating and reliable research into its wear mechanisms, a micro X-ray spectral analysis was carried out at magnification 400. Results of this study are shown in Fig. 7. Results of the micro X-ray spectral analysis of the points, indicated in Fig. 7, *b*, are given in Table 3. Thus, from Fig. 7, *a*, it is possible to draw a conclusion that the obtained films of friction surfaces are rather dense and uniformed, in the process of wear they are flaked both by large flat sections with the dimensions of 50–100 μm and by smaller ones. During studying the friction surfaces of coating in the secondary electrons, the uniformed structure of the films of trибointeraction is laminated into two phases – gray matrix and white inclusions with dimensions of 3–5 μm (Fig. 7, *b*). As it is shown by the results of micro X-ray spectral analysis of the points, indicated in Fig. 7, *b*, white inclusions are iron silicides of lower stoichiometric composition (spectra 1–3, Fig. 3, *b*). The gray matrix, in which these inclusions are located, is the compound mainly based on aluminum, silicon and oxygen (spectra 4–6, Fig. 7, *b*) with insignificant iron traces (up to 4 %).



a



b



c

Fig. 7. Microstructure ×400 of section of friction surface of plasma coating at 500 °C: *a* – in reflected electrons; *b* – in secondary electrons; *c* – surface topography with the indication of sections of micro X-ray spectral analysis at. % in Table 3

As a result of X-ray phase compositional analysis of the surface films of tribointeraction, the signals of Al_2SiO_5 compounds were found, which are aluminum silicate. In addition to Al_2SiO_5, separate oxides α-SiO_2, α-Al_2O_3, α-SiO_2, silicides of iron Fe_5Si_3, Fe_2Si and silicate Fe_2SiO_4 exist at the surface in smaller quantities. As a result, there is an effect of vitrification of friction surfaces. This, at a temperature of tribointeraction of 500 °C, slightly decreases the wear intensity of this coating to 50.84 μm/km, but considerably decreases the friction coefficient from 0.52 to 0.32.

Table 3

Results of micro X-ray spectral analysis of the points indicated in Fig. 7, *b**

Spectra	C	O	Al	Si	Fe	Ni
Spectrum 1	0.01	0.00	0.00	23.55	76.43	0.00
Spectrum 2	0.03	0.00	0.00	21.99	77.99	0.00
Spectrum 3	0.02	0.00	0.00	24.51	75.48	0.00
Spectrum 4	0.00	48.02	28.74	20.05	3.45	0.00
Spectrum 5	0.00	49.08	29.16	19.98	1.76	0.00
Spectrum 6	0.00	47.19	29.65	20.11	4.25	0.00

*Note: * – values are given in at. %*

Thus, as a result of analysis of the friction surfaces of the composite plasma coating on the steel counterbody without the lubricants at the elevated temperature of tribointeraction, it is possible to establish the action of the oxidizing wear mechanism and forming on the friction surface of the islet sections of glassy films of the triple oxide systems: oxides of aluminum, silicon and iron. The application of an intermediate sublayer of intermetallide nature made it possible to substantially increase the adhesion of coating to the steel surface under conditions of elevated temperatures.

6. Conclusions

1. We obtained new composite cermet plasma coatings of the (SiC–Al_2O_3)–$FeSi$ system on the medium-carbon steel with the adhesive sublayer from Ni_3Al. The structure of these coatings is the composition ceramic matrix Al_2O_3, in which the SiC grains and inclusions of phases on the basis of iron of silicides type are evenly distributed. The thickness of the coating varies in the limits of 100–140 μm.

2. The tribotechnical characteristics of plasma coatings within a wide range of load and speed parameters at elevated temperatures were explored. It was established that under the most severe accepted testing modes (R=4 MPa and V=7 m/s), the wear intensity of coating at a temperature of 250 °C reaches 53.57 μm/km, and friction coefficient is 0.52; at a temperature of 500 °C, the wear intensity of coating comprises 50.84 μm/km and friction coefficient amounts to 0.32.

3. The wear mechanisms of these coatings were established and it was found that the positive effect of stabilization of wear resistance of coating with an increase in temperature from 250 °C to 500 °C occurs due to vitrification of the friction surface and formation of aluminum and iron silicates at the surface.

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SELECTIVE ANODIC TREATMENT OF W(WC)-BASED SUPERALLOY SCRAP

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Вивчено анодну поведінку твердих сплавів ВК20КС, ВН8, ВНЖ, ВНДС. Показана можливість селективного анодного розчинення металевого зв'язуючого без окиснення твердого компоненту (вольфраму/карбіду вольфраму). Проведено гальваностатичну селективну анодну обробку лома твердого сплаву ВК20КС. Визначено склад вольфрам-вмісних продуктів: 23 % WO_3 або H_2WO_4, 73 % WC

Ключові слова: тверді сплави, пасивація, селективна анодна обробка, вольфрам, карбід вольфраму

Изучено анодное поведение твёрдых сплавов ВК20КС, ВН8, ВНЖ, ВНДС. Показана возможность селективного анодного растворения металла-связки без окисления твёрдого компонента (вольфрама/карбида вольфрама). Проведено гальваностатическая селективная анодная обработка лома твёрдых сплавов ВК20КС. Определен состав вольфрам содержащих продуктов: 23 % WO_3 или H_2WO_4, 73 % WC

Ключевые слова: твердые сплавы, пассивация, селективная анодная обработка, вольфрам, карбид вольфрама

1. Introduction

Superalloys are pseudo-alloys that are composed of W, WC or other solid components and binder metal (Ni, Co, Fe), that are manufactured by means of powder metallurgy [1, 2]. Superalloys possess high durability and heat resistance, which allows for their application in various fields: materials for drilling bit, high-speed cutters for steel processing,