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DETERMINING THE INFLUENCE OF THE MICROSTRUCTURE AND PHASE COMPOSITION OF GLASS-METAL-CERAMIC COATINGS ON THEIR BASIC PHYSICAL-TECHNICAL PROPERTIES

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Given the development of new heat-resistant nickel alloys that operate at temperatures up to 1,250 °C, as well as the introduction of additive technologies for the production of various parts, it is a relevant task to devise new compositions of highly heat-resistant coatings.

Determining the influence of the phase composition of glass-metal-ceramic coatings on its basic properties could improve the effectiveness of protecting those parts that operate under extreme conditions. Therefore, it is promising to conduct a study aimed at establishing the relationship between the microstructure and phase composition of glass-metal-ceramic coatings and the main physical-technical characteristics.

This study's results have established that the most high-quality coatings were obtained on the basis of non-crystallizing glass. Such glass is characterized by a temperature coefficient of linear expansion of $92 \cdot 10^{-7}$ degrees^{-1}, a glass transition temperature of 625 °C, and surface tension of $260 \cdot 10^{-3}$ N/m at 850 °C. These properties contribute to the formation of a defect-free coating, providing uniform spreading and high-quality adhesion to the substrate.

The resulting optimal coating is characterized by the adhesion strength of 98 %, the thermal resistance (mode 950↔20 °C) of 50 cycles, and the high heat resistance (a weight gain after 100 h in the temperature range of 1,000–1,050 °C) of 0.03 g/m$^2 \cdot$h.

Coatings with a minimum amount of glass bonding are distinguished by uniformity and high quality. The optimal ratio of phases "glass:metal-ceramic composition" is 10:90.

The structure of the recommended coating is uniform, characterized by the homogeneous distribution of components, the absence of cracks, visible defects, and high quality. The phase composition of the coating after firing is represented by crystals of metallic nickel and silicon, as well as a small amount of residual glass phase

Keywords: heat-resistant coating, coating microstructure, phase composition, heat-resistant alloys, gas corrosion, glass-metal-ceramic coating

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1. Introduction

Coatings are artificially created surface layers, which may differ from the base material in chemical and phase compositions, structure, and properties. Coatings are applied both to protect the surface from various types of influences (high loads, temperatures, various aggressive environments) and for decorative purposes and to restore the disturbed geometry of products, as well as to give special properties (to improve soldering, to give magnetic properties, etc.) [1].

Conditionally, all coatings can be divided into two types according to the principle of interaction with the surface:

1) change in the chemical composition of the surface (chemical and thermal treatment);

2) application of new material on the surface (spraying, deposition, surfacing, application of enamels and paints).

While the formation of diffusion coatings during chemical-thermal treatment is subject to general ideas about structural and phase transformations in metals and alloys, then the multifactor nature of coating processes leads to a more complex pattern of the structure and properties of the surface [1].

Glass-metal-ceramic coatings are heat-resistant and are designed to protect against high-temperature gas corrosion of special nickel alloys [2]. The introduction of such coatings makes it possible to improve the quality and reliability of parts operating under extreme conditions as a result of preventing oxidation and burnout of alloying components on the surface and along the boundaries of metal grains [3].

The widespread introduction of glass-metal-ceramic coatings is predetermined by the high manufacturability in comparison with most modern coating methods, which require complex special equipment. In addition, they are characterized by high adhesion to the protected metal during high-temperature firing, the possibility of applying complex configuration to the overall parts, continuity, slight porosity, high resistance to diffusion of gas medium components, etc. [4].

The search for new high-temperature coatings is associated, first of all, with the optimization of the chemical formulation of the compositions, as well as with the use of techniques for improving the structure and properties of both known and newly designed coatings [5]. Therefore, resolving this issue is a relevant and necessary task.

2. Literature review and problem statement

Paper [6] shows that the protection of metals and alloys by coatings is provided as a result of creating a barrier to aggressive agents. In the case of protective technological coatings, their interaction with the components of the protected alloys and the gas environment is no less important. Heat-resistant protective coatings are the result of high-temperature chemical reactions at the interfaces of the coating and alloy, in the coatings, and on their border with the gas environment, as well as thermal processes due to the nature of the coating materials. Such processes include the gradual softening of coating materials with a corresponding decrease in their viscosity, which predetermines the possibility of the gradual formation of a continuous protective layer and its wetting ability [7].

Depending on the production characteristics, high-temperature coatings can be divided into reactive-curable and reaction-sintered [8]. Such coatings, as well as refractory enamels, belong to the slurry-firing protective coatings. Their common features are the preparation of a hydraulic suspension (slurry) as the initial product, the application of hydraulic suspension on the protected surface, firing a pre-dried porous layer by heating the protected part at a predefined temperature. As a result of firing, a continuous refractory layer of coating is formed, firmly connected to the protected surface of the part.

It is established that the conditions for the formation of a continuous dense layer of coating, firmly linked to the substrate, are [9] the satisfactory solubility of the solid phase in the liquid; good wetting (spreading) of the liquid phase on the surfaces of solid particles and substrate. A prerequisite for obtaining a high-quality coating is the regulated dispersion of the solid phase of the coating, as well as a sufficient and moderate amount and uniform distribution of the liquid phase over the coating volume. With a lack of liquid phase and its uneven distribution, the adhesion of the coating with the substrate deteriorates. The excess liquid phase can increase shrinkage, reduce heat resistance.

Reaction-curable coatings are obtained by slurry-firing technology, based on glass, using chemical reactions whose result is the formation of a continuous protective layer at temperatures less than or equal to the operating temperature of the coating. Due to the chemical reactions of glass, the restrictions associated with unacceptably high firing temperatures of traditional coatings such as refractory enamels are eliminated [3].

Unlike silicate enamels, reactive-curable coatings after firing are characterized by stability, strength, and are not inclined to go into a viscous state when the operating temperature rises. The firing temperature of enamel is usually 200–300 °C higher than its maximum operating temperature. Given this, the use of conventional refractory enamels to protect heat-resistant alloys, for example, at gas flow temperatures of 1,200–1,250 °C, is problematic. Firing the coating at 1,350–1,550 °C is associated with de-hardening, deformation, and melting of the protected material. This limitation is eliminated by increasing the viscosity of glass coating due to chemical reactions in its volume. In addition, this is possible through the formation of a continuous protective layer of refractory frit during firing due to chemical reactions at moderate temperatures, rather than transferring to a viscous or plastic state [4, 8].

Reaction-curable coatings are currently not well understood. Such types of coatings are being intensively designed in order to improve the technological and operational properties [3, 4, 8].

Glass-metal-ceramic coatings are reaction-sintered. Coatings of reaction-sintered mixtures can be divided into two main groups in terms of their formulation:

1) containing silicate glass in the starting mixture;

2) capable of forming silicate glass during firing of the coating.

In the coatings of the first group, silicate glass serves as a bundle of particles of refractory oxygen-free compounds such as silicon carbide.

To obtain coatings of the second group, starting mixtures of B–Si–Cr–$MoSi_2$, Al–Si–B_2O_3, Nb–Cr–SiO_2 type are used [10, 11]. In the process of firing the coating, as a result of oxidation of boron, silicon, aluminum, borate, borosilicate, or aluminum-silicate, a liquid phase is formed on the substrate, which acts as a binder between the particles of refractory compounds and oxides. Coatings of this type were tested with positive results as protection against oxidation in the air at 1,400 °C and an exposure time to 100 and 500 h, on samples of titanium diborides, zirconium, niobium (100 h), hafnium, tantalum (100 h), etc. [12].

Currently, the literature has very limited information about the structure and phase composition of heat-resistant coatings of both types for the protection of special nickel alloys obtained by slurry-firing technology. Thus, the authors of [13, 14] investigated the structure formation of reaction-curable coatings. The presence of several stages of coating formation has been established: the formation of a macrostructure, accompanied first by the oxidation of tetraboride, and the formation of the liquid phase of borosilicate glass, then by softening of the matrix glass. After that, a microstructure forms, containing the phases of matrix glass, particles of modifying glass, and silicon tetraboride with interfaces visible at significant magnification. It is noted that during the operation of the coating, the level of properties is determined by the new bonds formed between barium-alum-silicate glasses, fusible borosilicate glass, silicon tetraboride, and the covalent Si-B bond is likely preserved.

Reaction-sintered coatings after firing contain vitreous and crystalline phases. The advantages of reaction-sintered coatings consist primarily in the fact that relatively simple techniques of slurry-firing technology, and at moderate firing temperatures, one can obtain very refractory and heat-resistant protective coatings on substrates with different metal bases. Regarding heat-resistant nickel-based alloys, the advantage of coatings is the possibility of forming protective layers at temperatures lower than the temperature of their operation [13].

The main advantages of glass-metal-ceramic thermal-protective coatings are the resistance to almost all aggressive environments, high strength, wear resistance, hardness, low density, as well as stability of mechanical properties in a wide range of temperatures [15]. Compared to conventional enamels, glass-metal-ceramic coatings withstand increased impacts [16]. In connection with the creation of new heat-resistant nickel alloys, operable at temperatures up to 1,250 °C [4], and the introduction of additive production technologies [17], it is a relevant task to design new compositions of highly heat-resistant slurry-firing coatings.

However, the issue of the influence of the phase composition of glass-metal-ceramic coatings on its basic properties remains unresolved. The reason for this may be the objective difficulties associated with the use of high-temperature glasses (T_{melt}>1,600 °C) as the base. An option for eliminating such a problem may be the use of a mixture of glasses of different refractory capacities. This approach is used in [18]. It is assumed that this could expand the temperature range of the protective action of the coating and adjust the viscosity of the layer. However, there is no systematic information on this issue in the literature.

All this suggests that it is advisable to conduct a study aimed at determining the relationship between the microstructure and phase composition of glass-metal-ceramic coatings and the basic physical-technical characteristics. Investigating this issue could make it possible to design heat-resistant coatings with improved performance characteristics and, thereby, increase the efficiency of protection of parts operating under extreme conditions.

3. The aim and objectives of the study

The purpose of this study is to establish the relationship between the microstructure and phase composition of glass-metal-ceramic coatings and the main physical-technical characteristics. This could make it possible to design new compositions of heat-resistant coatings and would improve the effectiveness of protection of parts operating under extreme conditions.

To accomplish the aim, the following tasks have been set:

– to study the influence of the chemical composition of base glasses and composite mixtures based on them on the basic physical-technical properties of coatings;

– to analyze the influence of the phase composition on the microstructure of coatings;

– to determine the phase composition and microstructure of the material with the best indicators of the values of the studied properties.

4. The study materials and methods

Experimental base glasses No. 1–3, and a metal-ceramic composition were used as starting materials to produce glass-metal-ceramic coatings. The ratio of the components "glass:metal-ceramic composition" was 10:90, 15:85, 20:80.

The charge of the metal-ceramic composition was prepared by mixing the starting powder components ($4Ni:1Si:0.5Al_2O_3:0.5TiB_2:0.1MoSi_2$) [17] in a ball mill until a homogeneous mixture was obtained and the mixture passed through a sieve No. 0063.

For the preparation of the charge of base glasses (Table 1), we used finely ground quartz sand and chemical reagents of qualification "chemically pure" and "pure for analysis" (boric acid, barium carbonate, alumina). Glass was boiled in corundum crucibles with a capacity of 100 ml in an electric furnace with silicon carbide heaters at a temperature of 1,150–1,450 °C for 60–120 minutes. Samples of glasses to determine their properties were made by casting melt glass into steel molds with their subsequent annealing in a muffle furnace at a temperature of 400 °C; the remainder of the glass mass was granulated by pouring on water.

The glasses, based on which the composite mixtures were composed, were previously crushed in a ball mill.

Experimental batches of slurry for coating were obtained by grinding a composite mixture of glasses with metal-ceramic components in a ball mill before passing through sieve No. 0063.

The surface of the samples of heat-resistant nickel alloy was prepared by sandblasting using electro-corundum, after which it was degreased with isopropyl alcohol. The compositions were applied to a metal substrate by pouring, dried in air at a temperature of 25±5 °C, then in a drying cabinet at a temperature of 80±10 °C for 1 h.

The choice of the firing temperature of coatings (850 °C) is due to the oxidation temperature of special nickel alloys without loss of mechanical properties. The firing time of the first layer of the coating is 1 h, the second – 0.5 h. Cooling of experimental samples was carried out in the air.

The nature of thermal transformations of raw materials and composite mixtures was studied by differential-thermal analysis using the derivatograph Q-1500D (Hungary), the heating rate of 5 °C/min.

The temperature coefficient of linear expansion (TCLE, α) and the glass transition temperature (T_g) were determined using an automatic quartz dilatometer DKV-5A.

The heat resistance of the coatings was determined by the number of thermal cycles (950–20) °C, which the samples withstand without destruction. The degree of destruction was estimated visually by the number of microcracks.

The adhesion strength of the coating to the metal was estimated by applying a shock load of 0.5 kgf/m with the calculation of the ratio of the chip area to the total area of the sample. The heat resistance of glass-metal-ceramic coatings was estimated according to GOST 9.312-89.

To study the microstructure of fired coatings, an optical microscope "Leica DMi8" (Germany) was used.

X-ray phase analysis of base glasses and glass-metal-ceramic coatings was carried out on the diffractometer DRON-3 (Russia) in Co-Kα radiation. To identify the crystalline phases, the ASTM radiometric database was used.

5. Results of studying the relationship between the microstructure and phase composition of glass-metal-ceramic coatings and the main physical-technical properties

5. 1. Studying the influence of the composition of base glasses and composite mixtures based on them on the main physical-technical properties of coatings

The necessary conditions [18] of effective protection of alloys are:

– formation of a continuous protective layer of coating at a relatively low temperature – to prevent intensive oxidation of the alloy in the initial stages of heating;

– dissolution of oxide films formed on the metal during heating, without loss of protective properties of the coating;

– sufficiently high viscosity and density of the protective layer – to reduce the diffusion of gases from the furnace atmosphere;

– strong adhesion of coatings with the alloy due to the formation of transitional diffusion layers, which predetermines the high reliability of operation of products under conditions of sharp temperature changes;

– general refractory capacity of the entire coating system – to ensure long-term operation of parts at high temperatures;

– the temperature and time parameters of coating formation should not reduce the mechanical properties of the alloy.

In addition, the formation of vitreous coatings on metal substrates is possible only in the case when the melt of glass at firing temperatures of coatings has a viscosity equal to 500–4,000 Pa·s. The value of the surface tension should be relatively small and be in the range of (200–300)·10^{-3} N/m [19]. The qualitative indicators of the resulting coatings (adhesion strength, continuity, etc.) also significantly depend on the values of their temperature coefficient of linear expansion (TCLE) [20].

In this regard, the glasses of the alkaline-free borosilicate system are of practical interest. A comprehensive analysis of the values of the temperature coefficient of linear expansion, glass transition temperature, the dilatometric temperature of softening of glasses [21] has allowed us to recommend glass types No. 1–3 as the base for obtaining a glass-metal-ceramic coating slurry (Table 1) [22].

The nature of the thermal transformations of the base glasses was estimated using differential-thermal analysis (Fig. 1).

Table 1

Basic properties of base glasses

Base glass No.	TCLE, $\alpha \cdot 10^7$, degree^{-1}	Glass transition temperature, T_g, °C	Surface tension [23], $\sigma_{850} \cdot 10^3$, N/m
1	83	485	240
2	104	650	340
3	92	625	260

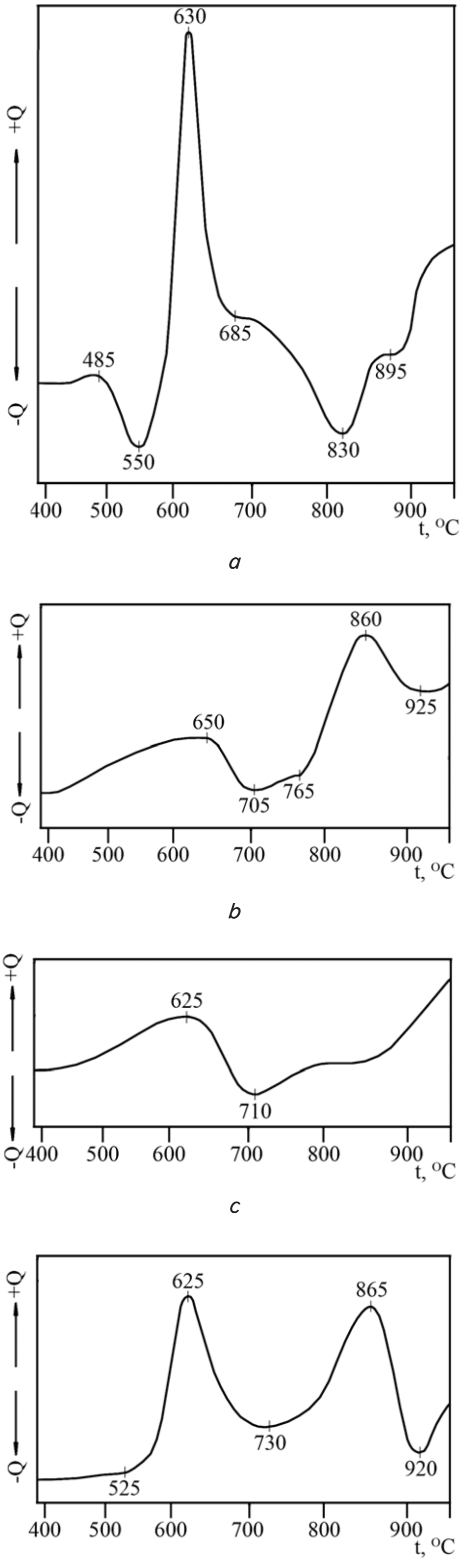
The thermograms of glasses No. 1, 2 demonstrate exoeffects in the temperature range of 550–685 °C and 765–925 °C, respectively, which indicates their crystallization. The crystalline-phase composition of these glasses is represented by the compounds BaB_2O_4 (Fig. 2) and $BaSi_2O_5$ (Fig. 3). The thermogram of the mixture of base glasses (Fig. 1, *d*) shows a decrease in the intensity of the first exoeffect of crystallization. The remaining effects represent the total contribution of each glass. It is assumed that the use of a mixture of base glasses of different refractories could expand the temperature range of the protective effect of the coating and adjust the viscosity of the layer. In addition, the presence of a crystalline phase in the glass would help increase the strength of the coating.

The absence of crystallization effects on the thermogram of glass No. 3 indicates the prerequisites for obtaining classical glass coating.

Thus, two types of basic glass ligaments were chosen for research: crystallizing mixture of glasses No. 1 and No. 2 of various refractory, and glass No. 3, characterized by a low tendency to crystallization.

Differential-thermal analysis of the metal-ceramic composition of the coating is shown in Fig. 4.

It was established that already at a temperature of 540 °C, almost to a firing temperature of 850 °C, intensive oxidation of the metal-ceramic component of the coating occurs. The oxidation process in a given temperature range is characteristic of metallic nickel, which prevails in the formulation of the metal-ceramic composition.



a

b

c

d

Fig. 1. Thermograms of base glasses powders:
a – glass No. 1; *b* – glass No. 2; *c* – glass No. 3;
d – a mixture of glasses No. 1 and No. 2 in a ratio of 1:1

Heat-resistant coatings, the composition of which is given in Table 2, are applied onto the surface of the parts in the form of a uniform layer of the predefined thickness.

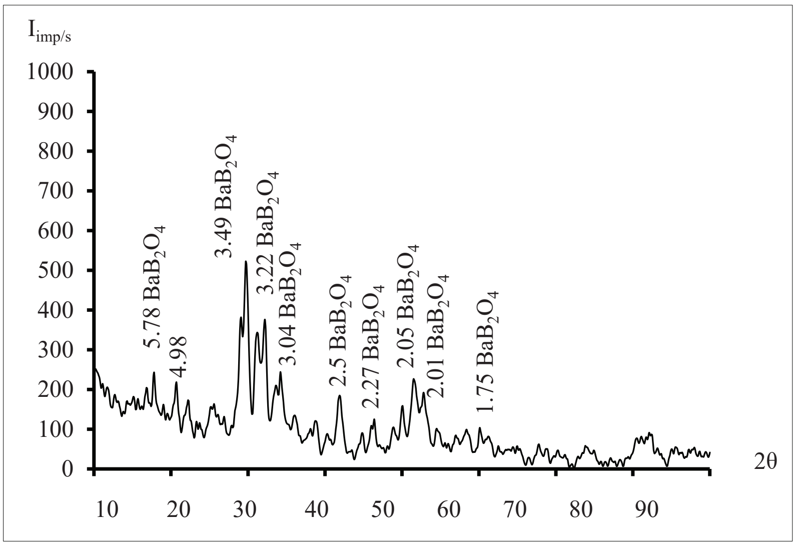


Fig. 2. X-ray diffraction pattern of crystallized glass No. 1 (crystallization temperature 630 °C, time — 1 h)

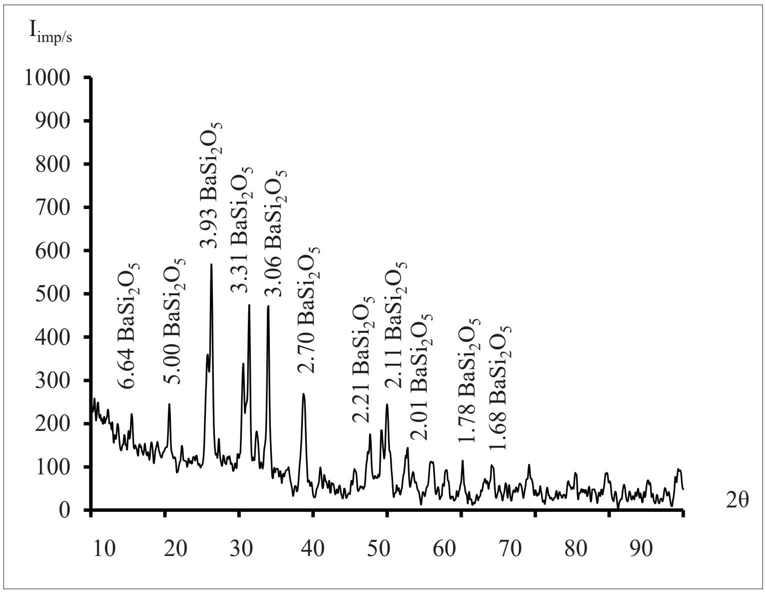


Fig. 3. X-ray diffraction pattern of crystallized glass No. 2 (crystallization temperature 860 °C, time — 1 h)

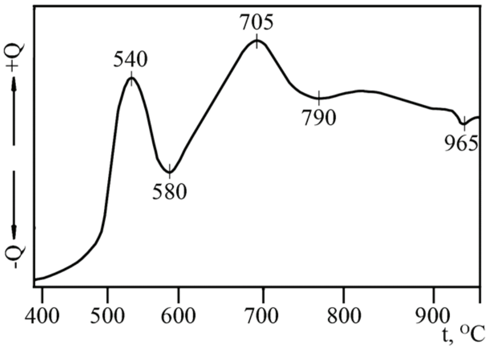


Fig. 4. Differential-thermal analysis of the metal-ceramic composition of the experimental coating

Coatings after firing should have a set of properties that guarantee the quality of the finished part: the absence of leaks, defects, multi-thickness, as well as continuity and density.

Table 2

Charge composition of experimental coatings, wt%

Composition No.	Glass No. 1	Glass No. 2	Glass No. 3	Metal-ceramic composition
1	5	5	–	90
2	7.5	7.5	–	85
3	10	10	–	80
4	–	–	10	90
5	–	–	15	85
6	–	–	20	80

The basic physical-technical properties of coatings are given in Table 3.

All obtained coatings are characterized by a thickness in the range of 130–150 µm. The maximum adhesion strength and heat resistance are demonstrated by the coating of composition No. 4. The minimum values of properties were obtained for coatings based on a mixture of base glasses No. 1 and No. 2.

Table 3

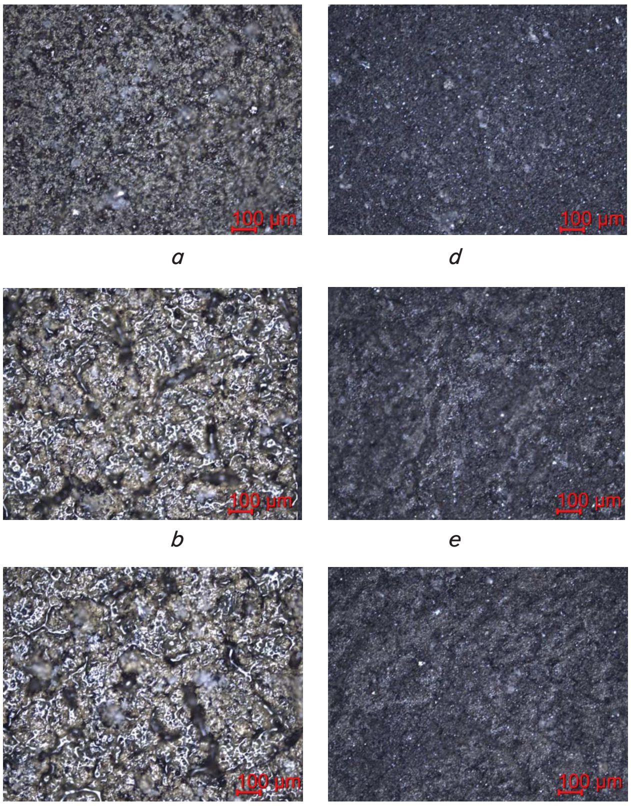
Basic physical-technical properties of prototypes

Composition No.	Two-layer coating thickness, µm	Adhesion strength, %	Thermal resistance (the number of cycles under the mode of 950↔20 °C)	Heat resistivity, g/m^2·h (a weight gain in the temperature range of 1,000–1,050 °C)
1	147	88	30	8.5
2	140	85	28	8.6
3	145	85	22	9.3
4	134	98	50	0.03
5	140	95	49	0.05
6	137	95	50	0.15

5. 2. Analysis of the influence of phase composition on the microstructure of coatings

The microstructure of the experimental coatings is shown in Fig. 5.

Coatings with a minimum amount of glass bonding are characterized by uniformity and high adhesion to the substrate. The green color of coatings No. 1–3 indicates the intensive oxidation of its metal components. With an increase in the amount of glass bonding from 10 to 20 wt %, there is the formation of local areas of the metal and amorphous components, which are aggregated by phase type (Fig. 6). This contributes to the deterioration of the surface quality and, consequently, the deterioration of the basic physical-technical properties of coatings (Table 1).



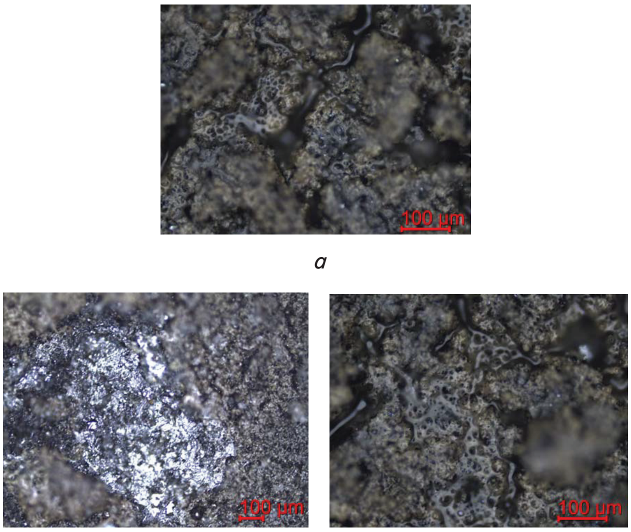
a *d*

b *e*

c *f*

Fig. 5. Microstructure of experimental coatings: *a* — coating No. 1; *b* — coating No. 2; *c* — coating No. 3; *d* — coating No. 4; *e* — coating No. 5; *f* — coating No. 6

It can be assumed that this is due to the unsatisfactory wettability of the components of the coating with glass base and a significant difference in the values of surface tension.



a

b *c*

Fig. 6. Microstructure of experimental coatings: *a* — coating No. 2; *b, c* — coating No. 3

Coatings obtained on the basis of glass No. 3, in general, are of good quality and have no cracks. A comprehensive analysis of the structure and basic physical-technical properties allows us to recommend the composition of coating No. 4 for further study.

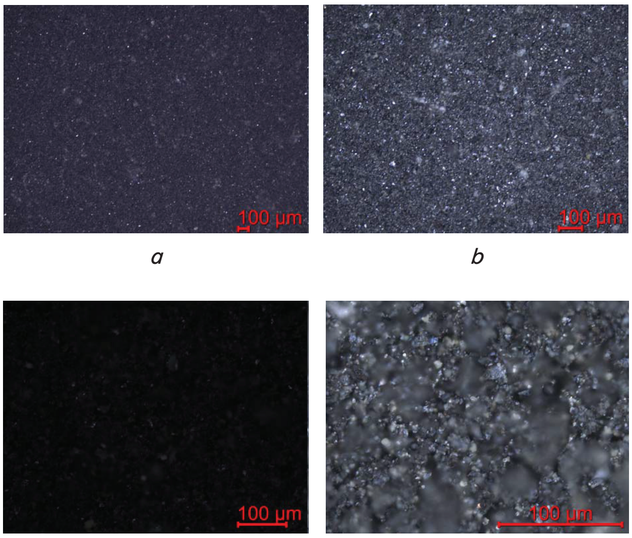
5. 3. Determining the phase composition and microstructure of the material with the best indicators of the values of the studied properties

The microstructure of coating No. 4 is shown in Fig. 7.

The structure of coating No. 4 is characterized by uniformity, the homogeneous distribution of components, the absence of cracks, visible defects, and has high quality. Even though the amount of glass phase here is minimal and is 10 wt %, these coatings are characterized by an adhesion strength of 98 %. At the same time, their thermal resistance (mode 950↔20 °C) is 50 cycles, and heat resistivity (a weight gain after 100 hours in the temperature range of 1,000–1,050 °C) is 0.03 g/m^2·h. These property indicators fully meet the requirements that are imposed on heat-resistant coatings of special alloys [12].

The crystalline-phase composition of experimental coating No. 4 (firing temperature, 850 °C) is shown in Fig. 8.

It should be noted that, despite the treatment of the coating in the temperature range of intensive oxidation of nickel (Fig. 2), the main crystalline phases are represented by nickel and silicon. The absence of nickel oxide on the diffractogram is most likely due to its small amount and is within the range of experiment error (~5 %). Apparently, the oxidation process of the metal components of the coating is limited by the presence of the glass phase, which envelops the metal particles. Thus, the access of oxygen to them slows down. In addition, a small amount of the resulting nickel oxide should have a positive effect on the adhesion strength of the coating with the substrate.



a *b*

c *d*

Fig. 7. Microstructure of the experimental two-layer coating No. 4 (firing temperature, 850 °C) at different magnification: *a* – at ×125; *b* — at ×250; *c* — at ×500; *d* — at ×1,250

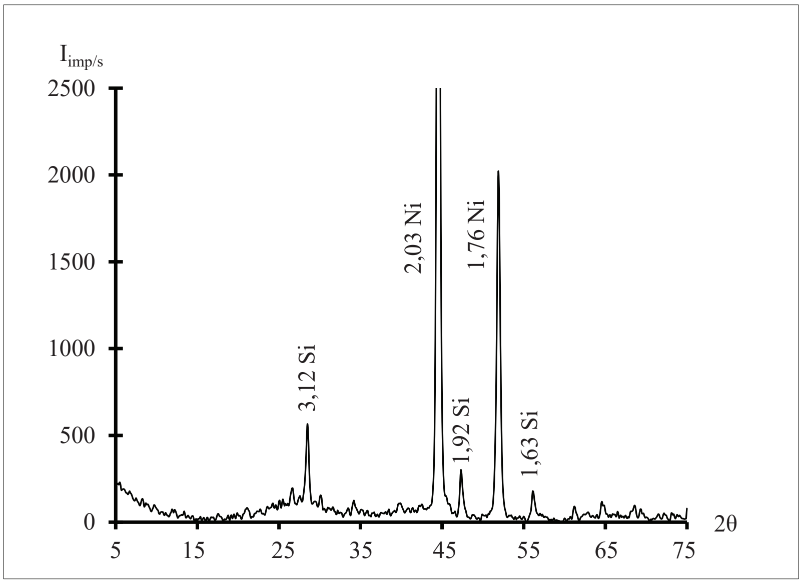


Fig. 8. X-ray diffraction pattern of the experimental coating of composition No. 4 (firing temperature, 850 °C; firing time, 1.5 h)

The selected heat treatment time is enough to form a high-quality coating and does not lead to undesirable intensive oxidation of metal components in the coating. The residual glass phase is represented on the diffractogram by a small amorphous halo.

6. Discussion of results of studying the relationship between the microstructure and phase composition of glass-metal-ceramic coatings and the main physical-technical properties

During our research, the relationship between the structure, phase composition, and basic physical-technical properties of heat-resistant glass-metal-ceramic coatings for special-purpose alloys was established. As a base, we used glass bonding consisting of a mixture of 1:1 of crystallizing glasses No. 1, 2 of different refractory (Table 1, Fig. 1, *d*). The second glass bonding was a classic amorphous, non-crystallizing refractory glass No. 3 (Table 1, Fig. 1, *c*). The amount of glass bonding in the coating ranged from 10 to 20 wt % in increments of 5 wt % (Table 2). The formulation of the metal-ceramic composition of the coating was not changed (Fig. 4). Experimental coatings were applied in layers by pouring twice with subsequent firing. Manufacturability of slurry application depending on the phase composition of coatings did not change. The choice of the temperature-time mode of firing coatings (850 °C) is due to the oxidation temperature of special nickel alloys without loss of mechanical properties.

The most qualitative uniform structure of coatings was obtained with a minimum amount of injected glass bonding (Fig. 5, *d*). Moreover, the use of a mixture of crystallizing glasses (Fig. 2, 3) of different refractory has a negative effect on the formation of the structure of coatings, forming local areas of the components of the composition of different nature (Fig. 6). This contradicts work [16] on the effectiveness of using a mixture of base glasses of various refractory capacities to increase the protective properties of heat-resistant coatings. The noted also negatively affects the values of the basic physical-technical properties of glass-metal-ceramic coatings, reducing them to unacceptable limits (Table 3). As an advancement of our study, it is possible to use a mixture of base glasses of different refractory capacities, not prone to crystallization, or composition of glasses of different nature.

On the contrary, the use of glass No. 3 leads to the formation of a defect-free high-quality coating (Fig. 7). To obtain a homogeneous uniform layer, the introduction of 10 wt % of the base glass bonding No. 3 would suffice. An increase in the amount of the latter leads to a slight decrease in the main physical-technical characteristics. Thus, the strength of the adhesion is reduced by 3 %, the thermal resistance practically does not change, and the heat resistance decreases by 5 times (Table 3).

Thus, the optimal, according to the totality of the studied characteristics, is the glass-metal-ceramic coating No. 4, which consists of 10 wt % of glass No. 3 and 90 wt % of metal-ceramic composition. The microstructure of such a coating is characterized by uniformity, the homogeneous distribution of components, the absence of cracks, visible defects, and high quality. The crystalline phase composition of the coating is represented mainly by nickel and silicon, as well as a small amount of residual glass phase (Fig. 8). The optimal coating is characterized by adhesion strength of 98 %, the thermal resistance (mode 950↔20 °C) of 50 cycles, and the heat resistance (a weight gain after 100 h in the temperature range of 1,000–1,050 °C) of 0.03 g/m^2·h.

7. Conclusions

1. We have established the influence of the chemical composition of base glasses and composite mixtures based on them on the basic physical-technical properties of coatings. The most high-quality coatings were obtained on the base of the non-crystallizing glass, which is characterized by $\alpha=92\cdot10^{-7}$ $degree^{-1}$, $T_g=625$ °C, and $\sigma_{850}=260\cdot10^{-3}$ N/m. These properties contribute to the formation of a defect-free coating, providing uniform spread and high-quality adhesion to the substrate. The resulting coating is characterized by the adhesion strength of 98 %, the thermal resistance (mode 950↔20 °C) of 50 cycles, and the heat resistivity (a weight gain after 100 h in the temperature range of 1,000–1,050 °C) of 0.03 g/m^2·h.

2. The influence of phase composition on the microstructure of coatings has been established. Coatings with a minimum amount of glass bonding are characterized by uniformity and quality. With an increase in the amount of basic crystallizing glass bonding from 10 to 20 wt %, there is the formation of local areas of the crystalline and amorphous components, which are aggregated by phase type. This contributes to the deterioration of the surface quality and, consequently, the deterioration of the basic physical-technical properties of the coatings. Coatings obtained on the basis of non-crystallizing glass bonding are distinguished by the absence of defects on the surface. The optimal ratio of phases "glass:metal-ceramic composition" is 10:90.

3. The structure of the recommended coating of composition No. 4 is characterized by uniformity, the homogeneous distribution of components, the absence of cracks, visible defects, and high quality. The phase composition of the coating after firing is represented by crystals of metallic nickel and silicon, as well as a small amount of residual glass phase.

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