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A MODIFIED METHOD OF APPLYING DETONATION-SPRAYED COMPOSITE COATINGS BY A MAGNETIC FIELD

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Досліджено структуру та основні властивості покриттів із композиційного матеріалу, що містить зносостійку складову SiC-Al_2O_3 та металеву зв'язку на основі заліза, отриману в результаті розмелу вихідних елементів композиції у сталевих барабанах. Покриття наносили детонаційним методом на середньовуглецеві сталі та модифікованим методом у штучно наведеному магнітному полі. Досліджено вплив магнітного поля на структуроутворення покриттів зазначеного складу та основні характеристики покриттів

Ключові слова: композиційне покриття, детонаційне напилення, магнітне поле, адгезія. тугоплавка складова, металева зв'язка

Исследована структура и основные характеристики покрытий из композиционного материала, содержащего износостойкую составляющую SiC-Al_2O_3 и металлическую связку на основе железа, полученную в результате размола выходных элементов композиции в стальных барабанах. Покрытие наносили детонационным методом на среднеуглеродистые стали и модифицированным методом в искусственно наведенном магнитном поле. Исследовано влияние магнитного поля на структурообразование покрытий указанного состава и основные характеристики покрытий

Ключевые слова: покрытие, композиционный материал, детонационное напыление, магнитное поле, адгезия, тугоплавкая составляющая, металлическая связка

1. Introduction

The problem of improving the durability and corrosion resistance of machine parts is topical for the equipment functioning at high speeds and loads. Ceramic composite materials of high wear resistance are very promising in such working conditions. These materials are also resistant to effects of aggressive environments. Such requirements are met by ceramic composites based on silicon carbide and aluminum oxide, which have high physical and mechanical properties and are inexpensive and non-scarce materials.

An important advantage of using composite coatings is obvious due to a great complexity of modern machine parts and a large range of materials for their production: the use of expensive composite ceramics locally in the form of a surface coating is significantly economical, and it allows a flexible use of surface and bulk properties of the parts.

2. Literature review and problem statement

Ceramic and metal-ceramic materials have proved their undeniable advantages long ago for using them as protective coatings [1]. Their application as a local surface hardening significantly reduces the amount of using these materials [2], and this is essential because they are rather costly. According to the experience of applying various ceramic materials, their value primarily depends on their physical and mechanical properties: namely, the cheaper are the components of the composition, the lower are the coating properties, and the more expensive and energy intensive is the technology of applying them [3]. However, profound examining of the physicochemical properties and the effects of applying and forming the structure of the coatings by means of a gradual optimization can help determine structural and technological measures that will allow achieving significant results when using cheap and common components [4]. These components are silicide carbide and aluminum oxide [5].

Silicon carbide materials have been known for more than half a century [6] and, due to the high physicochemical properties and a relatively easy production, the interest in their use does not subside even today. In [7], research is described on selecting an optimal composition of a metallic and ceramic bundle and a more suitable method for applying the wear resistant silicon carbide coatings.

For applying ceramic powder composite materials to steel surfaces by thermal methods, it is necessary to introduce the metal component into the charge to ensure an adhesive bundle between the ceramics and the steel backup as well as a cohesive bundle between the phases of the coating. The introduction of the metal bundle in the ceramic composition also significantly reduces energy consumption and simplifies the selection of optimal regimes for the coating.

The SiC-Al_2O_3 ceramic material is chosen as a wear-resistant composite component for applying detonation-sprayed coatings. It has been previously tested as a compact ceramic material with a high level of tribotechnical characteristics [8]. The traditional introduction of a metal bundle has certain technical difficulties such as the low resistance of silicon carbide in metal melts and its intensive interaction with the silicate formation. It has been determined that the strengthening silicon carbide phase actively interacts with the one-component melts to form silicate as a result of hot pressing. It has been further revealed that during the agglomeration of the charge for applying the coating the ceramic phase SiC-Al_2O_3 is milled as being more friable, whereas the artificially introduced metallic component becomes, unfortunately, only plastically deformed without changing the size. Moreover, as there is a double or even triple difference in weight between the ceramic and metal particles of the charge, it easily delaminates and its strengthening phase gets lost in the process of applying the coating.

The size factor significantly affects the processes of friction and wear of ceramic materials. In particular, particles of silicon carbide and aluminum oxide of more than 5 µm are good abrasive materials; particles of less than 5 µm are friction media, which reduce the intensity of wear. So the ceramic component of the coating must have the smallest particle size. It is also known that the most efficient method of grinding silicon carbide and aluminum oxide is to use planetary-type mills in drums with grinding bodies in dispersed liquid media [9]. However, to avoid the grinding effect, it is advisable to use lined drums and ceramic grinding bodies, and this in turn leads to a significant increase in the time of grinding since ceramic grinding bodies are significantly lighter than steel ones.

Given the above described features of the structure of silicon carbide coatings with a metal bundle, it is suggested to apply an innovative approach of introducing the metal bundle into the SiC-Al_2O_3 composition, which entails obtaining metallic additives in the process of grinding and mixing this composition in the steel drums with steel grinding bodies. It will allow introducing iron in the charge; when it is artificially introduced into the charge, it does not get ground in this system. This composition can be used as wear-resistant coatings on medium-carbon steel. The chosen method of coating is a detonation spraying method, which allows obtaining high-density coatings being characterized by a low temperature effect on the component and a powder composition.

3. The purpose and objectives of the research

The purpose is to obtain silicon carbide composite coatings for medium carbon steels to ensure improved functional properties.

To achieve this purpose, it is essential to do the following tasks:

1) to study the formation of the powder composition of initial components in the process of grinding and to study the morphology of the particles;

2) to obtain coatings from the studied powder composition by the method of detonation and to research their composition and structure;

3) to study the influence of a magnetic field on the structure of the given coatings and their basic properties.

4. Materials and methods of the research

The experiments were carried out by using modern equipment and devices that had been tested and calibrated by metrological support services. The samples were processed carefully before and after the experiments.

Aluminum oxide powders (TU 6-09-2486-77) with an average size of 40–45 µm and silicon carbide with an average size of 45–50 µm of the 64C brand (GOST 26327-84) at a concentration of 50 % SiC – 50 % Al_2O_3 (mass) were mixed in steel drums with steel grinding bodies in the planetary-type mill “Sand 1” in an acetone medium for 32 hours. The obtained charge was dried and sieved. Methods of a chemical analysis were involved to determine the quantity of the ground iron, which was 19.3 % by weight.

The coatings were applied by the detonation facility “Dnipro-3M” (Fig. 1). This machine determined the optimum modes of applying detonation-sprayed coatings in terms of the thickness and surface of the coating. It was estimated that the obtained composition should be applied under the following conditions: the working gas should be a mixture of C_2H_2-O_2; the consumption of C_2H_2 is 30 points, and the use of O_2 is 70 points; the powder supply should be 30 points. The blowing of the barrel at the end of the cycle is to be with air; the lift gas is air. The rate should be 4 shots per second. The diameter of the spot is 22 mm. The spraying distance is to be 170 mm. The effect of a constant magnetic field was researched using a cylindrical solenoid at the exit from the tube, which provided a magnetic field intensity of H=150 A/m.

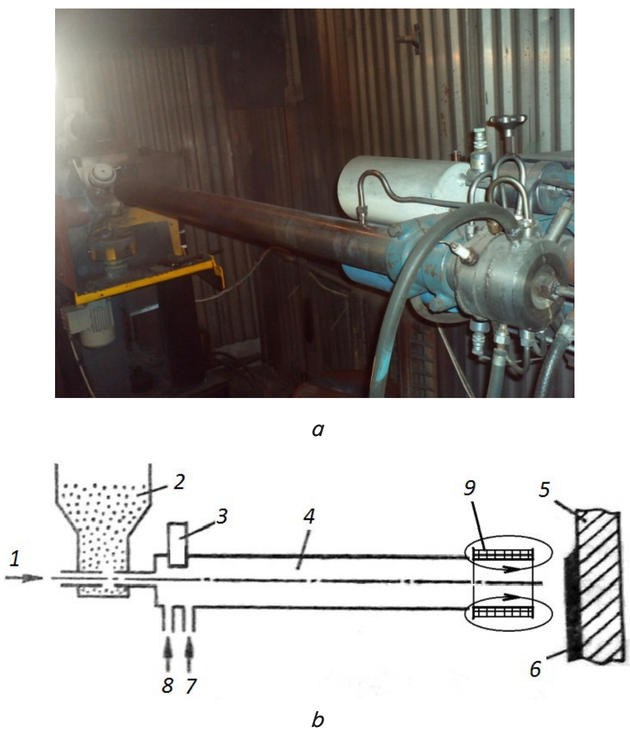


Fig. 1. The main captions: *a* is the detonation facility "Dnipro-3M"; *b* is its simplified basic skeleton: 1 is a bearing gas; 2 is a charge tank; 3 is a spark plug; 4 is the facility tube; 5 is a padding (template); 6 is the coating; 7 is the blowing gas between shots; 8 is a combustible gas; 9 is a solenoid coil

The coating was applied to the surface to analyze the adhesion, residual stress, and metallographic properties for the thickness of 175 μm, with the time of applying being 8 seconds. The adhesion of the coating to the substrate was measured by a pin method (Fig. 2).

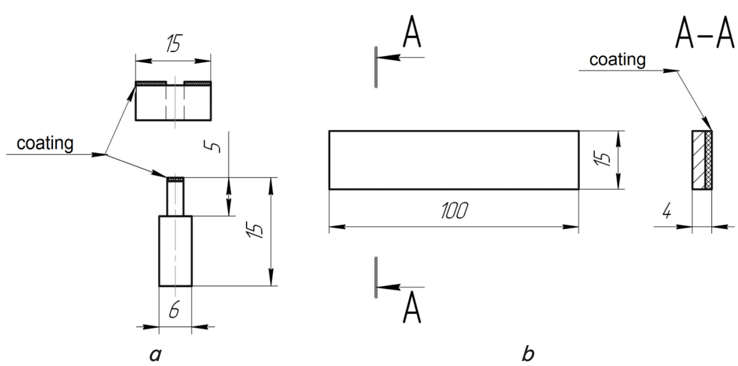


Fig. 2. Templates for the coatings: *a* — to test the coating adhesion; *b* — to study the structure and metallographic properties

The structures of the charge powders and the detonation-sprayed coatings of the composite material (SiC-Al_2O_3)-Fe were studied by an electron microscopy method, using the scanning electron microscope REM-106Y and the X-ray diffraction analyzer DRON-3.0 (USSR).

5. The results of researching the initial charge

The results of the research on obtaining the initial charge for a coating after grinding are shown in Fig. 3 and Table 1. Thus, even after 1 hour of grinding, the average diameter of the particles is reduced by half, and the milled iron is 1.5 %. After 16 hours of grinding, the particles size stabilizes at 2.2 μm, and the milling is 16.3 %. A further doubling of the experiment duration does not significantly affect the average particles size or the milling.

Table 1

The characteristics of obtaining the initial charge for gas-thermal coatings depending on the time of grinding

Time of grinding, hrs	1	2	4	8	16	32
Average size of the charge particle, μm	28.7	14.9	6.8	4.8	2.2	2.1
Content of the milled iron, % mass	1.5	3.4	6.8	10.9	16.3	19.3

The microradiography and the spectral analysis of the initial powders of the charge after 1 hour of grinding in the steel drums and with steel grinding bodies (Fig. 3, *a–c*) in the charge revealed the iron particles in the quantity of 1.5 %, and the average particle size was 1.3–1.7 μm (Fig. 3). It is significantly smaller than the average particle size of the ceramic component. The particles in the charge are distributed evenly; however, it should be noted that there is a significant formation of iron particles with the size of 4–8 μm (Fig. 3, *a*). In the process of further grinding of the charge for 16 hours, the average particle size gradually stabilizes at being 2.1 μm; the iron particles are gradually integrated into larger clusters of unequal weight (Fig. 1, *d*) with a length of the greater axis being 6–8 μm.

Fig. 3, *d* can produce a conclusion that the concentration of iron particles significantly increases to 16.3 % (Table 1). The increased zooming of up to 10,000 reveals (Fig. 1, *f*) that along with the clusters of iron particles sized 6.8 μm there were found iron nanoparticles sized 492 nm and micro-dispersed particles sized 1.33 μm. The research findings show that such a diverse-size factor of iron particles, which are commensurate with ceramic particles and micro-dispersed particles, prevents the delamination of the charge into the metal and ceramic parts in the magnetic field. The whole mass of the charge is moving in a steel "matrix", all ceramic particles get scavenged, and the constant magnetic field does not result in more than a 1–2 % loss of the ceramic component of the charge. Due to these reasons, the research was undertaken to explore the influence of the constant magnetic field on the structure formation of detonation coatings in the given charge.

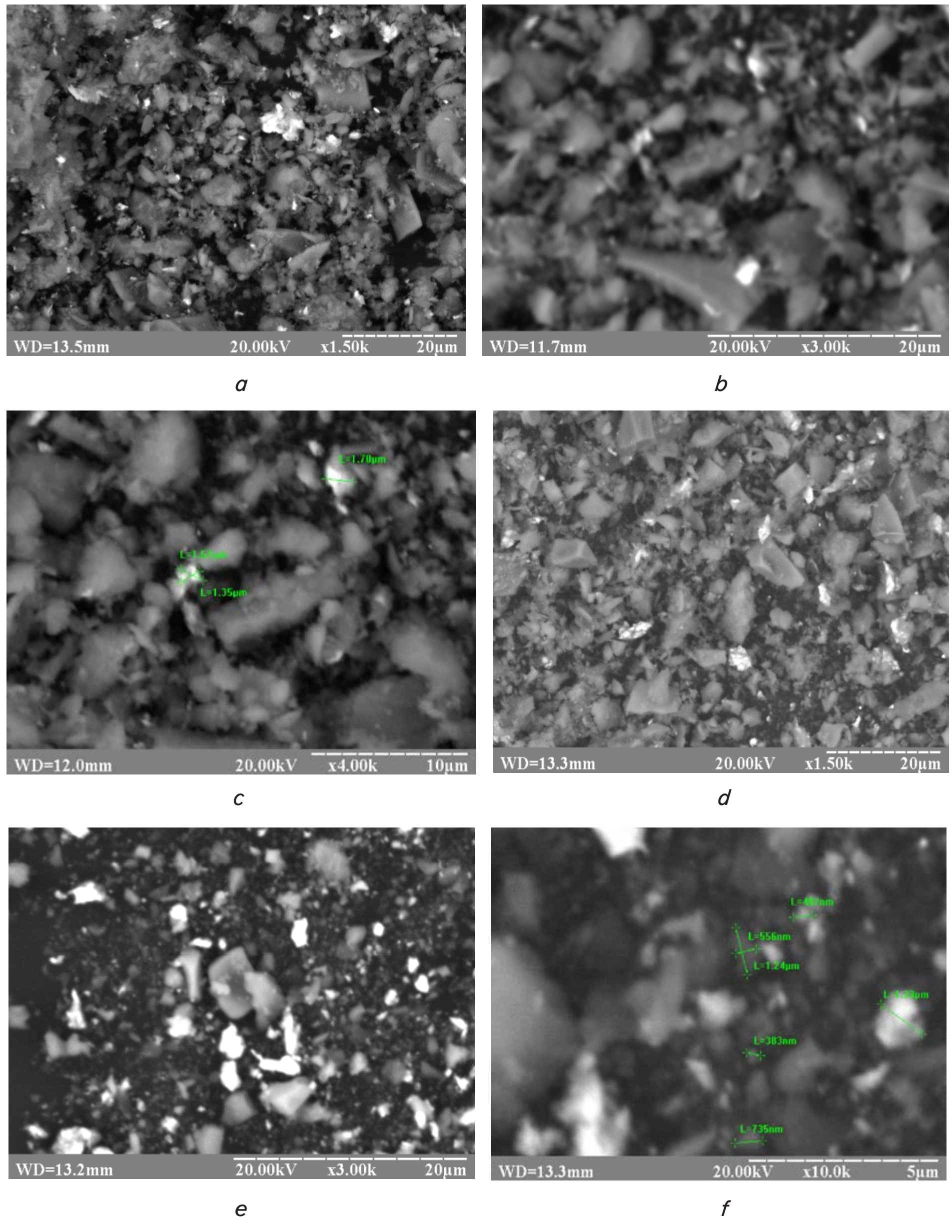


Fig. 3. Electronic microscope photos in secondary electrons of the powders of the SiC-Al_2O_3 composition after mixing and grinding in a steel drum by steel bodies: *a*, *b*, and *c* for 1 hour; *d*, *e*, and *f* for 16 hours; the photos are zoomed: *a* and *d* – 1,500; *b* and *e* – 3,000; *c* – 4,000; *f* – 10,000

6. Discussion of the research results

Most researchers dealing with silicon carbide coatings [1, 3, 6] have more than once remarked that an independent application of silicon carbide with activating additives by using various thermal methods involves significant technological challenges. Sedimentation of the refractory elements of the charge as well as their burn out and residue in the dump are low. All this requires additional technological measures and a careful study of their impact on the coating properties such as porosity, uniformity, and adhesion to the substrate surface.

Scientists have also researched adding metal components to the silicon carbide composition, which does not always produce a favorable effect on the content of the silicon carbide phase in the final coating due to two factors. The first factor is a significant chemical activity of silicon carbide in metal melts with an instant silicide and free carbon formations: although they are released in the form of flaky graphite inclusions, it adversely affects the integrity of the coating. The silicide formation itself in large quantities is negative as silicides have significantly lower physical and mechanical properties. The second factor is a significant difference in the density of the refractory components and metal connections in the charge, which causes its componential segregation in the process of accelerating by gas-thermal methods. It also adversely affects the content of the silicon carbide phase in the coating and significantly worsens the uniformity of the coating structure. Therefore, we have suggest and tested our own innovative method.

In [10], there is an assumption that the effectiveness of processing the surface of any magnetic composition can be significantly improved if a constant magnetic field is applied to the axis of the particles' motion so that unequal particles of the composition can be directed along the lines of the force, which will significantly improve the collision force throughout the processed surface. Therefore, in the framework of this research, a study has been carried out on the impact of the magnetic field on the structure and basic properties of detonation-sprayed coatings of the given composition. For this reason, the deliberately chosen gas-thermal method is detonation, which does not significantly increase the temperature of the charge components, and the iron particles do not reach the Curie point temperature when the iron loses its magnetic properties. The charge that had been obtained after 16 hours of grinding (Fig. 3, *d–f*) was used to apply the coating by 30 shots with an external magnetic field and without it. The structure of such coatings is shown in Fig. 4.

A completely different picture is observed when applying the given composition in the medium of the magnetic field (Fig. 4, *d–e*). First of all, there is a significant increase of the coating at the same quantity of shots from the detonation gun, so the coating thickness is 150–180 µm. The structure of the coating is homogeneous, without substantial and visible stratifications (Fig. 4, *d*). The porosity of the coating is less than 3 % (Fig. 4, *f*). The transition boundary between the coating and the substrate is continuous and without significant faults, which is likely to improve the adhesion of the coating quite substantially. The adhesion of the coating is 7 MPa.

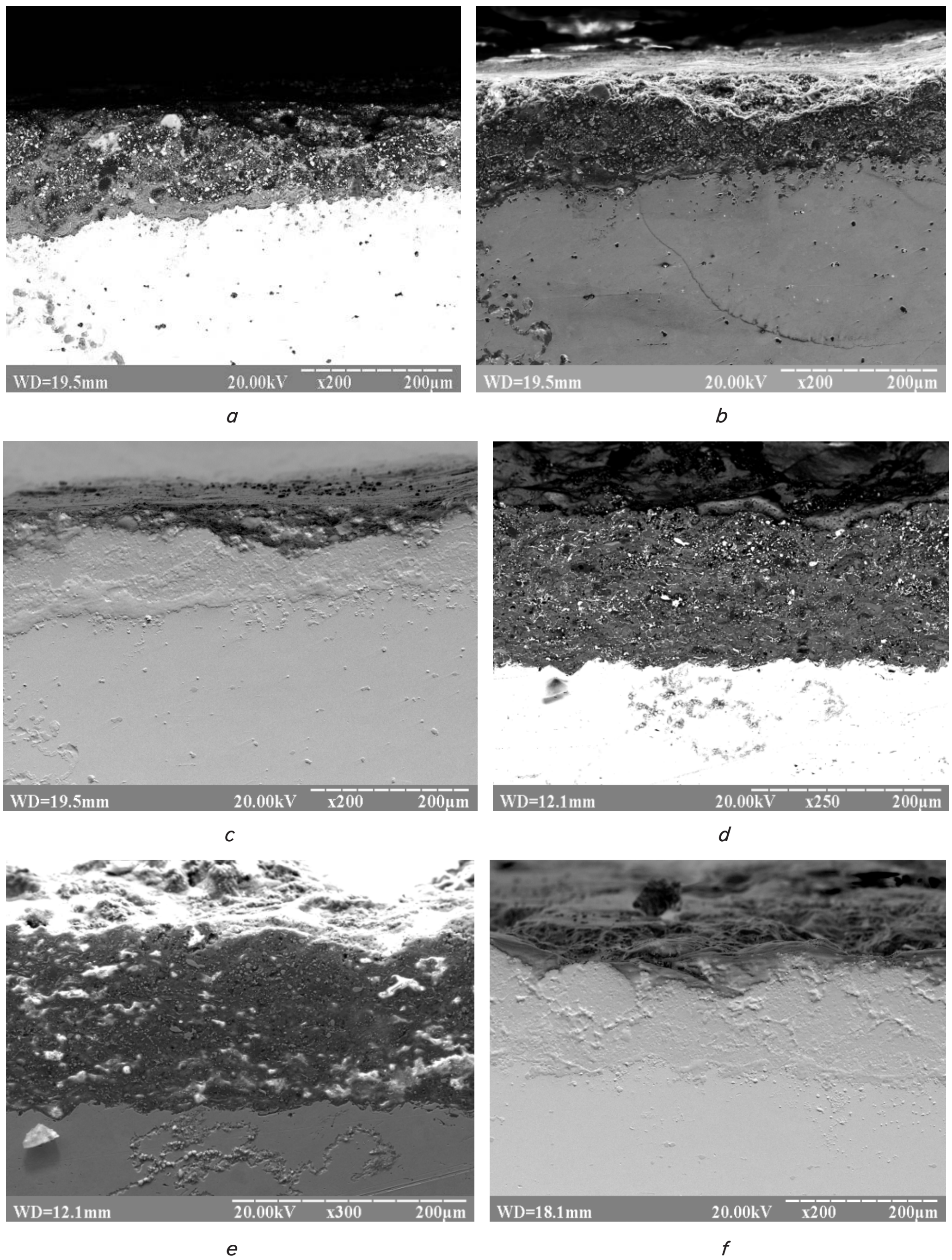
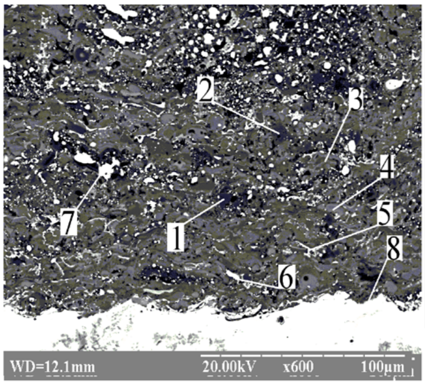


Fig. 4. Electronic microscope photos of detonation-sprayed coatings of ($SiC–Al_2O_3$)–Fe, zoomed 200: *a* and *d* – in elastically reflected electrons; *b* and *e* – in secondary electrons; *c* and *f* – as layer surface topography after 30 shots from a detonation gun; *a*, *b*, and *c* – without a magnetic field; *d*, *e*, and *f* –with a magnetic field targeted at the exit of the detonation gun

The coating microstructure (Fig. 5) is a composition material consisting of a matrix on the basis of aluminum oxide in which SiC particles are distributed evenly.



Spectrum	C	O	Al	Si	Fe
Spectrum 1	47.53	–	–	52.47	–
Spectrum 2	41.11	–	–	57.89	–
Spectrum 3	–	54.02	45.98	–	–
Spectrum 4	–	53.03	46.97	–	–
Spectrum 5	–	–	–	33.66	76.34
Spectrum 6	–	–	–	19.23	80.77
Spectrum 7	0.03	45.18	–	14.65	40.14
Spectrum 8	0.04	–	_	–	98.99

Fig. 5. The coating microstructure of (SiC-50 %Al_2O_3)-Fe with the specified points of the composition material under an X-ray analysis

Possible pores in the ceramics are filled with iron-based phases, and their structure equals the structures of silicates and iron silicides (Fig. 5) This is reconfirmed by the X-ray analysis, which has revealed SiC, Al_2O_3, SiC, Al_2O_3, $Fe_{1.34}$, $Si_{0.66}$, Fe_3Si, and Fe_2SiO_4 in the coating phase, indicating possible chemical reactions during an intense shock interaction between the particles of the charge and the substrate. The coating thickness varies from 150 µm to 170 µm. The size of the ceramic particles varies from 3 µm to 10 µm. A conclusion can be made that chemical transformations in the initial components of the charge are minor.

7. Conclusions

1. The study has determined that the process of grinding the initial components of the system (SiC-Al_2O_3) in a steel drum for 32 hours produces 19 % of milled iron in the charge; the revealed broad size spectrum ranges from 400 nm to 1.5 µm. Moreover, the larger particles are non-equal in size, which leads to a conclusion that the impact of the magnetic field in the case of a gas-thermal application of the charge is positive.

2. The tests have produced new metal-ceramic composite detonation-sprayed coatings of the system (SiC-Al_2O_3)-Fe made on relatively cheap components of medium-carbon steel. The structure of the coating composition is a ceramic Al_2O_3 matrix in which the SiC grains are evenly distributed, and the inclusions of the phases are based on silicides and silicate irons. The coating thickness varies from 150 µm to170 µm.

3. The research has revealed a positive impact of an external constant magnetic field on the structure formation and the application of composite denotation coatings of the system (SiC-Al_2O_3)-Fe. The magnetic field significantly enhances the spreading capacity of the covering by almost 1.5 times and the coating adhesion capacity by 5 times. It is also worth noting that when a constant magnetic field is used during the coating application, the porosity of the surface is significantly reduced.

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