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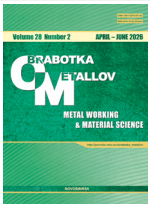

Electric arc surfacing using flux-cored wire with titanium carbide filling

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ABSTRACT

Introduction. To extend the service life of components exposed to abrasive particles during operation, wear-resistant coatings are applied to their working surfaces using powder spraying or various surfacing methods. One of the simplest and most accessible surfacing techniques is arc surfacing in air. To improve the productivity of this process, flux-cored wire is used instead of stick electrodes. ***Subject.*** This paper describes the technology for producing a composite powder for flux-cored wire manufacturing, and presents the equipment used for wire fabrication and arc coating surfacing. ***The purpose of the work*** is to investigate a composite powder synthesized from a mechanically activated mixture of ferrotitanium (*FeTi35Si5*) and carbon black (soot), as well as the wear-resistant coatings deposited by arc surfacing onto a steel *0.09 C–Mn–2 Si* substrate using a low-carbon steel *0.08 C–Al* wire with a composite powder core. **Methods.** The powder and the arc-surfaced coatings were characterized by optical metallography, scanning electron microscopy (*SEM*) with energy-dispersive X-ray spectroscopy (*EDS*) for elemental composition analysis, and X-ray diffraction (*XRD*). The surfaced coatings were tested for abrasive wear according to *GOST 23.208–79*, and the microhardness of both the powder and the coatings was measured. The composite powder used as the core filling in the flux-cored wire was obtained by crushing sintered cakes — the products of reaction synthesis in a mechanically activated powder mixture of ferrotitanium (*FeTi35Si5*) and carbon black, processed in an *Activator-2S* ball mill. Specialized equipment was used for flux-cored wire fabrication and for electric arc surfacing. **Results and Discussion.** According to *XRD* analysis, the powder synthesized from the mechanically activated ferrotitanium–carbon black mixture contains two phases: titanium carbide (*TiC*) and **α**-iron (ferrite). Metallographic examination revealed that the synthesized powder exhibits a structure characteristic of an iron-matrix composite reinforced with nanosized carbide particles. The coating surfaced using the flux-cored wire has the same phase composition, but with a reduced titanium carbide content. The coating features a martensite-like microstructure, exhibits 4.5 times higher hardness and 2.5 times higher abrasive wear resistance compared to a coating surfaced with a solid *0.08 C–Al* steel wire (without powder filling). ***Conclusions.*** Electric arc coatings surfaced with flux-cored wire filled with an iron-matrix composite powder exhibit high hardness (6,629 ± 498 MPa) and abrasive wear resistance (158 ± 11 mg/h) due to the martensitic structure of the surfaced layer, which is additionally reinforced by micron-sized titanium carbide particles. During surfacing, the submicron titanium carbide particles present in the composite powder structure undergo complete dissolution, enriching the weld pool with carbon and promoting martensitic transformation upon cooling.

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Introduction

The main goal in the development of new compositions and technologies for structural steel and alloy production is to increase strength while maintaining acceptable ductility. However, a major disadvantage is the low abrasive wear resistance of these materials. To increase the service life of parts exposed to dry friction and abrasive wear under operating conditions, wear-resistant coatings are applied to the work surfaces. Powder spraying and various surfacing methods are commonly used to deposit these coatings. Detonation [1–3] and plasma spraying [4–6] are two of the most frequently used methods.

In gas thermal spraying methods, a high-speed jet of gases or plasma accelerates the feedstock powder. In most cases, the components of the powder mixture react with each other or with the carrier gas [7, 8]. Sometimes the interaction is used for in-situ synthesis of refractory compounds, the particles of which increase the hardness and wear resistance of the coating. However, powders with a high affinity for oxygen can oxidize, including due to the ingress of ambient air. As a result, porosity increases and the adhesion of the coating to the substrate decrease.

In the cold gas dynamic spraying (*CGDS*) method [9, 10], powder heating occurs mainly upon impact with the substrate; therefore, the problem of powder oxidation is less significant. Due to the lower heating temperature, *CGDS* is mainly used for low-melting-point powders, such as aluminum and its alloys.

The disadvantages of powder spraying methods include increased porosity of the coatings and insufficient adhesion to the substrate. To eliminate these disadvantages, the sprayed coatings are either additionally melted [11, 12] or compacted during the spraying process – for example, with an ultrasonic impactor [13] or by burnishing [5]. Additional consolidation operations for sprayed coatings complicate and increase the cost of the technology. Therefore, surfacing methods are often used to obtain thick, non-porous coatings with reliable adhesion to the substrate. An electric arc [14], low-temperature plasma [15], low-energy [16] or high-energy (relativistic) electrons [17] are used as a heating source. In recent decades, lasers have been widely used to form the surfacing melt pool.

Metal matrix composite coatings reinforced with uniformly distributed solid particles of refractory compounds (mainly carbides and borides) provide the greatest increase in wear resistance. Mechanical mixtures of metal and refractory compound powders are used as feedstock in powder surfacing. Tungsten carbide is often used as a dispersed reinforcing phase in metal matrix composites. It has a lower hardness compared to other metal carbides, but higher ductility, which prevents brittle fracture under mechanical load. To form a metal binder (matrix), powders of metals such as nickel, iron, titanium, aluminum alloys, and complex alloys known as high-entropy alloys are used.

Among the surfacing methods mentioned above, electric arc surfacing in air is the most straightforward and accessible. It does not require specialized equipment or a vacuum. To prevent oxidation, arc surfacing is carried out under a flux layer. To increase the productivity of the arc surfacing process, a flux-cored wire is used instead of stick electrodes. The flux-cored wire is a thin-walled tube made from low-carbon steel filled with a powder [18]. The powder composition is selected to ensure the elemental and phase compositions of the surfaced coating and the required service characteristics in terms of hardness, wear resistance, corrosion resistance, etc. Currently, a wide range of flux-cored wires are produced as commercial products. Equipment for flux-cored wire production is also available.

To avoid segregation of metal powders and refractory compounds with different densities and particle sizes, composite powders in granulated form are used instead of powder mixtures. The composite granules contain a particulate reinforcing phase and a metal binder in the required ratio. This approach eliminates the segregation problem associated with the use of powder mixtures as feedstocks.

The most technologically advanced and cost-effective method for producing composite powders for surfacing and spraying is self-propagating high-temperature synthesis (*SHS*) in reactive powder mixtures. The self-sustaining exothermic reaction is easily realized in powder mixtures containing titanium and carbon. This is due to the fact that the titanium carbide synthesis reaction has a large negative enthalpy. Metal-binder powders in the reaction mixture act as a thermally inert dopant [19–22]. The resulting synthesis product contains titanium carbide particles as a reinforcing phase in the metal matrix. The formation of refractory compound particles can also occur in-situ at the time of the spraying or surfacing processes [23, 24].

A significant cost reduction of *SHS* composite powders can be achieved by replacing expensive titanium powder in the reaction mixtures with significantly more affordable ferrotitanium. It was found that in mechanically activated reaction mixtures of *FeTi35C5* ferrotitanium and carbon (*P-803* carbon black), synthesis can be initiated in combustion wave or thermal explosion mode [25]. After milling the synthesis products (cakes), composite powder granules consisting of titanium carbide particles in an alloyed ferrite matrix were obtained. Based on these results, we have patented [26] a high-performance method for producing low-cost ferromatrix composite powders for spraying and surfacing wear-resistant coatings.

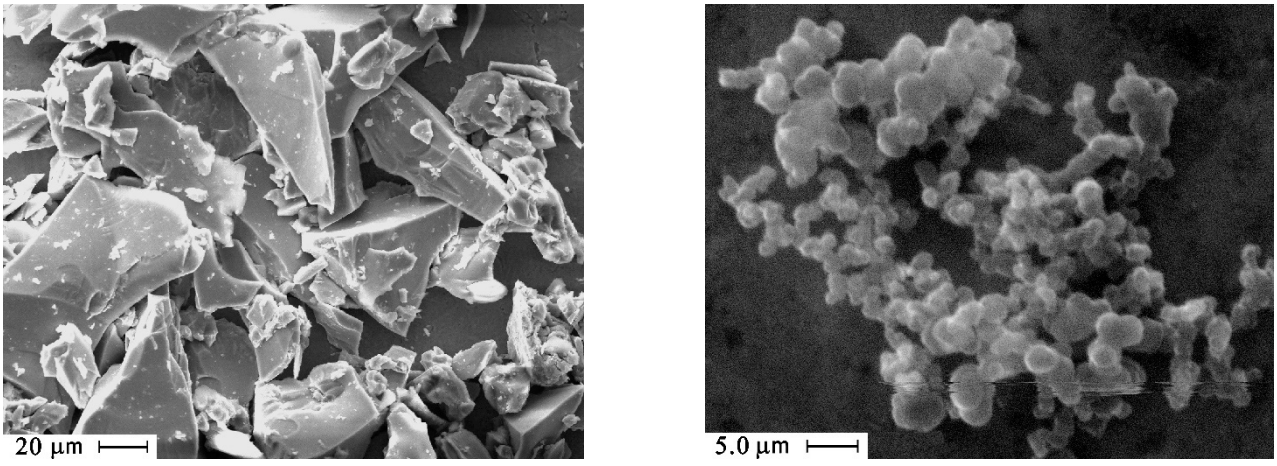
The purpose of this study was to investigate the structure and properties of coatings obtained by electric arc surfacing using a flux-cored wire filled with a composite powder synthesized from mechanically activated mixtures of ferrotitanium and carbon black. The practical aim was to determine the economic and technological feasibility of using synthesized composite powders to produce flux-cored wire for arc surfacing of wear-resistant coatings.

Materials and methods

Flux-cored wire materials

To synthesize the composite powder for flux-cored wire production, *FeTi35C5* ferrotitanium powder (*GOST 4761-91*) with a particle size of less than 50 μm and *P-803* carbon black (*GOST 7885-86*) were used. Fig. 1 shows the morphology of the used powders. Powdered ferrotitanium was produced by milling and sieving ferrotitanium lumps into fractions. As a result, ferrotitanium particles with an irregular (fractured) shape were obtained (Fig. 1,*a*). *P-803* carbon black consisted of agglomerates of submicron particles (Fig. 1, *b*).

A strip of low-carbon steel (*0.08C-0.07Al*, *GOST 1577-2022*), alloyed with aluminum, was used as the shell of the flux-cored wire. The substrate for surfacing was a plate of low-alloy silicon-manganese *09Mn2Si* steel with a thickness of **10 mm** and a carbon content of less than 1 wt.% (*GOST 19281-2014*). Table 1 shows the chemical composition of the materials used.



a *b*

Fig. 1. SEM images of the morphology of the initial powders:
a – FeTi35Si5; *b – P-803* carbon black

Table 1

Chemical composition of the studied materials, wt.%

Grade	*Fe*	*Ti*	Al	Si	C	Cu	V	Mo	*Zr*	*Ni*	*Mn*	*Cr*
FeTi35Si5 ferrotitanium	Bal.	32.45	9.75	4.65	0.18	0.85	0.88	0.35	0.15	–	–	–
Steel *0.08 C–0.07 Al*	Bal.	–	< 0.07	0.01	< 0.07	< 0.06	–	–	–	< 0.06	< 0.35	
Steel *0.09 C–Mn–2 Si*	Bal.	–	–	< 0.8	< 0.12	< 0.30	–	–	–	< 0.30	< 1.7	0.30

Methodology of composite powder production

The *TiC* + α-*Fe* composite powder was synthesized from a powder mixture containing 92.5 wt.% ferrotitanium and the balance carbon black. Carbon concentration (7.5 wt.% carbon black) in the reaction mixture was determined based on the assumption that the amount is sufficient to bind the titanium present in ferrotitanium into carbide. The mixture was treated in a high-energy laboratory planetary ball mill *Activator-2S* (*Chemical Engineering Plant, Ltd.*, Russia) at a rotation speed of 960 rpm, corresponding to an angular acceleration of 64 g, for a processing time of 10 min. The ratio of the mass of the balls to the total mass of the mixture was 20:1.

The mechanically activated (*MA*) powder mixture was pressed under 550 MPa in a cylindrical mold with a diameter of 28 mm. A blind hole was drilled in the compacts, into which a *WRe20*/*WRe5* tungsten-rhenium thermocouple was placed. When the compacts were heated in a vacuum furnace at a rate of 6 °C/min up to 450 °C, a sharp temperature spike was observed. This abrupt temperature increase was a sign of a thermal explosion in the powder mixture. The compact was heated to 700 °C, held for 60 minutes, and then the furnace was turned off. The resulting cake (synthesis product) was crushed and sieved into fractions. The 315–2,000 μm fraction was used as a feedstock in the production of flux-cored wire.

Methods of structural research and testing

A *0.08C-0.07Al* steel strip with a width of 14 mm and a thickness of 0.5 mm was bent in the form of a groove, which was filled with the powder mixture and drawn through a drawing die (Fig. 2, *a*). As a result, the edges of the strip were tightly joined, preventing powder leakage through the joint. The finished wire (Fig. 2, *b*) with a diameter of 4.3 mm was used for electric arc surfacing using specialized equipment – an *ASAW-1250* welding machine (Fig. 2, *c*). The technical specifications of the *ASAW-1250* machine are shown in Table 2.

In accordance with *GOST 9087-81*, an *AN-26C* welding flux was used for surfacing in air. Three layers were surfaced using a current of 420 A, a voltage of 38 V, and a surfacing speed of 18 cm/min. After surfacing, the flux crust was removed, and the surface of the coating was cleaned with a wire brush.

To assess the effect of the powder feedstock on the structure, hardness, and wear resistance of the coatings, an additional coating was surfaced with a tubular wire without powder filling, i.e., an empty *0.08C-0.07Al* steel shell.

Methods of structural research and testing

Structural studies of synthesized composite powders and surfaced coatings were carried out using the equipment at the *Shared Use Center "Nanotech"*, ISPMS SB RAS. Optical metallography (*AXIOVERT-200MAT*, *Zeiss*, Germany) and X-ray diffraction analysis (*DRON-7*, *Burevestnik*, Russia) were used. The study was carried out using *Cu-Kα* radiation (**λ** = 1.54186 Å). A point-resolution detector was used. The exposure time at a 0.04° step was 15 seconds, and the scanning range was from 30 to 85 degrees. The sample was rotated at a speed of 0.5 rpm during exposure**.** The *MAUD* software and the *Qualitative and Quantita-*

a *b* *c*

Fig. 2. General view:

a – equipment for flux-cored wire manufacturing; *b* – fabricated wire; *c* – *SAW-1250* automatic arc welding tractor

Table 2

Technical specifications of *ASAW-1250* automatic arc welding machine

Parameter	Value
Supply voltage (V)	380
Input power (kV·A)	54
Input current (A)	120
No-load voltage (V)	*SAW*: 90 ± 10; *MMA*: 75 ± 5
Arc voltage (V)	20–50
Welding current range (A)	60–1250
Welding current at 100% duty cycle (A)	1250
Protection class	*IP* 23
Efficiency (%)	92
Dimensions ($L \times W \times H$) (cm)	767 × 352 × 802
Rated supply voltage (V)	120
Rated output power (kV·A)	0.4
Wire diameter (mm)	1.6–6.0
Welding speed (cm/min)	10–150
Wire feeder speed (m/min)	0.3–3.0
Vertical adjustment of the welding nozzle (mm)	100

tive Phase Analysis based on COD were used to determine the phase composition and calculate the mass ratio of phases using the *Rietveld* method. In addition, scanning electron microscopy (*LEO EVO 50*, *Zeiss*, Germany) was used for phase identification.

Samples for metallographic studies of the powders and surfaced coatings were embedded in epoxy resin. The sections were prepared using a *Saphir-520/530* grinding and polishing machine (*Mager Scientific, Inc.*, Germany). Emery papers with a particle size range of 5–200 μm and diamond pastes with particle sizes of 3–0.5 μm were used. After polishing, the samples were cleaned in a *CODYSON CD-4830* ultrasonic bath (*Shenzhen Codyson Electrical Co., Ltd.*, China). The treatment was carried out in ethyl alcohol at a temperature of 40 °C for 15 minutes with degassing enabled. To reveal the structure of the surfaced coatings, the sections were etched with a 4 vol.% solution of HNO_3 in ethanol at room temperature and kept in the reagent for 30–40 seconds. To measure the hardness, an *ITV-1-I-MC* microhardness tester (*Metrotest, Ltd.*, Russia) was used. The measurements were carried out using the *Vickers* method with a load of 200 g and a loading and unloading time of 10 seconds each. Over 250 indentations were made at a constant spacing of 150 μm, directed from the substrate toward the coating surface along five parallel lines.

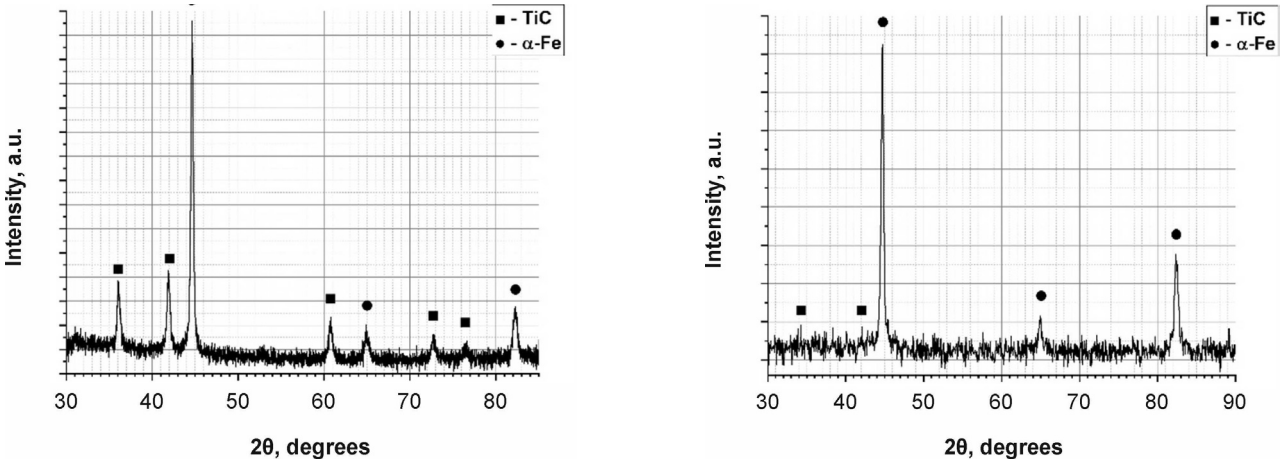
Tests of the deposited coatings for abrasive wear were carried out in accordance with *GOST 23.208-79 Wear Resistance Testing of Materials by Friction against Loosely Fixed Abrasive Particles* [27]. The test sample was worn out using *No. 16-P* electrocorundum abrasive particles with a particle size range of 160–200 μm, which were fed into the friction zone using a rotating rubber roller.

Results and discussions

Phase composition

Fig. 3 shows X-ray diffraction patterns of the synthesis products and the surfaced coating. Table 3 presents the results of the X-ray diffraction data analysis.

TAccording to the X-ray diffraction analysis of the powder obtained from a mechanically activated ferrotitanium and carbon black mixture, two phases were identified: titanium carbide and α-*Fe* (Fig. 3, *a*). The lattice parameter of titanium carbide (***a*** = 0.43153 Å) was less than the reference value for equiatomic



a *b*

Fig. 3. X-ray patterns:

a – composite powder synthesized from a mechanically activated mixture of *FeTi35Si5* ferrotitanium and carbon black and *b* – coating surfaced with the flux-cored wire containing the composite powder

Table 3

Processing of X-ray diffraction data analysis

Pattern	*TiC* (*FCC*, *Fm-3m*)		**α**-*Fe* (*BCC*, *Im-3m*)	
	Content (vol. %)	Lattice parameters (nm)	Content (vol. %)	Lattice parameters (nm)
Synthesized powder	52.49 ± 0.92	0.43153	47.51 ± 1.38	0.286650
Surfaced coating	5.69 ± 2.13	0.4326378	94.31 ± 0.5	0.28727
Reference data of the lattice parameters (nm)		0.43270		0.28730

titanium carbide, which is ***a*** = 0.43270 Å [23]. The reasons for the difference may be a deviation from the equiatomic composition or oxygen contamination.

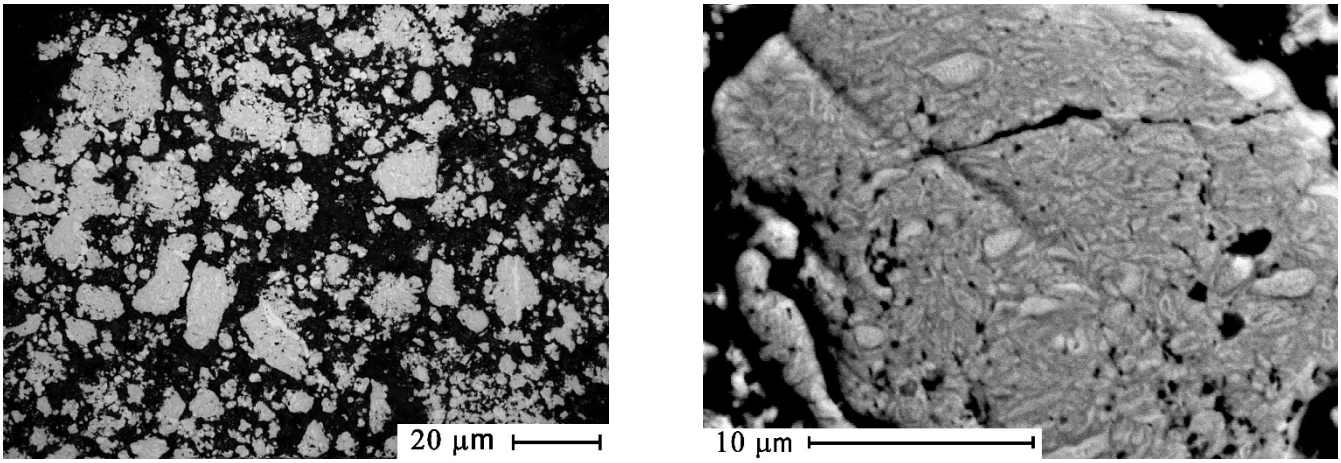
Based on an analysis of the available data on the dependence of the titanium carbide lattice parameter on its composition, in the first case the composition corresponds to $TiC_{0.65}$, while in the second case it is an oxycarbide of composition $TiC_{0.6}O_{0.4}$ [24].

The lattice parameter of α-*Fe* (***a*** = 0.28727 Å) is very close to the reference value (***a*** = 0.28730 Å). Probably, alloying elements such as *Ti*, *Al*, and *Si* present in the ferrite exert a mutually compensating effect on the lattice parameter.

Microstructure of powder and surfaced coating

The microstructure of granules of *TiC* + 47.5 vol.% α-*Fe* composite powder obtained by crushing the synthesis products from the ferrotitanium and carbon black powder mixture is shown in Fig. 4, *b*. Due to phase contrast in *BSE* images, titanium carbide and the iron-based binder can be identified. The light binder areas in the composite powder granules exhibit a bimodal size distribution: a few rounded inclusions ranging from 0.5 to 1.5 μm in size and smaller needle-like inclusions in the size range of 0.15–1.0 μm. Within the large binder areas, there are equiaxed gray carbide inclusions 50–100 nm in size. Thus, carbide and the iron-based binder are present in the composite as a submicron mixture of two structural elements.

Formation of the submicron structure of the composite is possible due to solid-phase synthesis in mechanically activated ferrotitanium and carbon black powder mixtures. The maximum temperature increase during a thermal explosion did not exceed 1,000 °C [25]. The temperature of the subsequent one-hour exposure at 700 °C was insufficient for the diffusion growth and coagulation of the nanoscale particles formed during the thermal explosion.

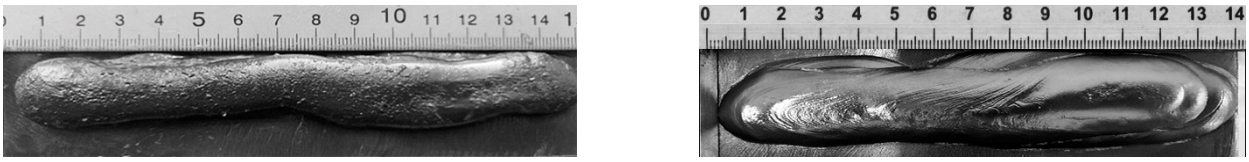


a *b*

Fig. 4. Microstructure of composite powder particles synthesized from a mechanically activated mixture of *FeTi35Si5* ferrotitanium and carbon black:
a – optical image of particles; *b* – backscattered electron (*BSE*) image

For electric arc surfacing, the flux-cored wire produced from the synthesized composite powder and a *0.08C-0.07Al* steel shell using the above method was used. Fig. 5 illustrates the appearance of the coating surfaced using the flux-cored wire and the tubular wire without powder filling, i.e., the unfilled steel shell.

The surfaced coatings differ in terms of surface roughness and width-to-height ratio. The coating surfaced using the flux-cored wire (Fig. 5, *a*) has a rougher surface and a higher height-to-width ratio than the coating surfaced using tubular wire without powder filling (Fig. 5, *b*). Due to lower spreadability, the coating surfaced using the flux-cored wire filled with the composite powder has a greater thickness: up to 9 mm compared to 6 mm for the coating surfaced using tubular wire without powder filling.



a *b*

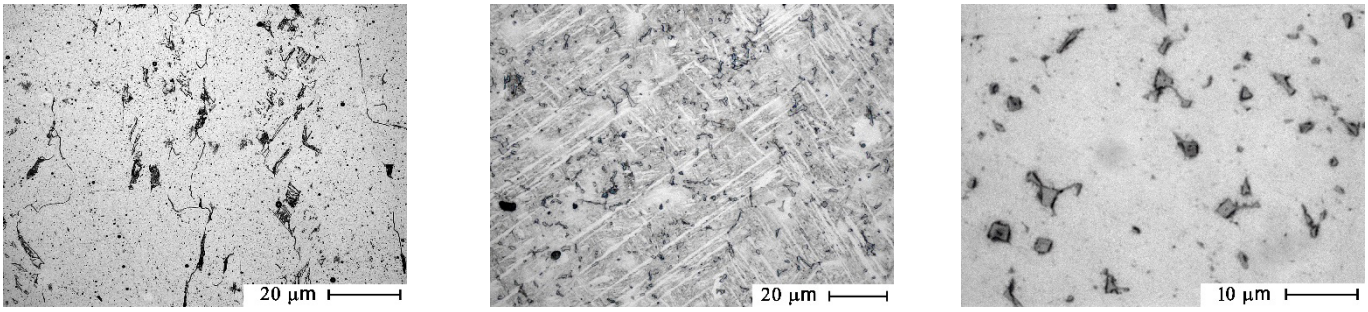
Fig. 5. Images of beads deposited with:
a – flux-cored wire; *b* – tubular wire without powder filling

According to the X-ray phase analysis results (Fig. 3, Table 3), the coating surfaced using the flux-cored wire filled with the composite powder has the same phase composition as the powder. However, the volume fraction of titanium carbide in the surfaced coating is significantly decreased due to its dissolution in the iron-diluted surfacing bath, as the *0.08C-0.07Al* steel shell is almost entirely composed of iron.

Fig. 6 shows the microstructure of the coatings after etching the sections with a 4 vol.% solution of HNO_3 in ethanol. The coating surfaced using the low-carbon tubular *0.08C-0.07Al* steel wire without powder filling consists of ferrite and pearlite inclusions (Fig. 6,*a*).

A quantitative assessment of the relative volume fraction of pearlite was carried out by measuring the area of pearlite inclusions on the etched sections using *Image J* software. The volume fraction of pearlite was additionally estimated assuming that the carbon content in the steel sheet is 0.08 wt.% and in pearlite is 0.8 wt.%. The results of metallographic analysis showed that the volume content of pearlite in the electric arc coating deposited using tubular wire without powder filling is 9.37 ± 1.27%, which is consistent with the estimated value (10%).

Etching of the coating surfaced using the composite powder-filled wire reveals a martensite-like needle structure (Fig. 6, *b*). Faceted titanium carbide inclusions uniformly distributed in the steel matrix can be seen in the non-etched sections (Fig. 6, *c*).



a *b* *c*

Fig. 6. Optical microscopy images of the microstructure:
a – tubular *0.08 C–0.07 Al* steel wire surfacing; *b* – *TiC* + **α**-*Fe* flux-cored *0.08 C–0.07 Al* steel wire surfacing;
c – *TiC* + **α**-*Fe* flux-cored *0.08 C–0.07 Al* steel wire surfacing (non-etched structure)

The structural features of both coatings and the microhardness depend only slightly on the distance from the substrate, except for a thin 300-μm boundary layer. The thickness of the boundary layer is about 3% of the total coating thickness. Average microhardness values of the coatings are given in Table 4.

Taking into account the high hardness of the coating (6,629 ± 498 MPa), we assume that it is indeed martensite. Due to the carbon-rich surfacing bath, martensite transformation is possible under conditions of rapid cooling of the surfaced coating. When titanium carbide, which constitutes about 50 vol.% of the composite powder, dissolves in the melt, carbon transfers to the surfacing bath. Taking into account the submicron size of the carbide inclusions in the composite powder and the sufficiently large volume of the cladding bath during the surfacing process, one can assume that the carbide phase of the composite powder completely dissolves in the melt.

According to numerous published data, the dissolution of feedstock titanium carbide in the melt of the surfacing bath during the coating process has been confirmed. As a result of carbide phase dissolution, a liquid solution of carbon and titanium in iron is formed. When the surfacing bath is cooling, faceted titanium carbide particles precipitate out of the liquid solution (Fig. 6,*c*). The remaining carbon and titanium pass into the α-*Fe*-based solid solution.

For a better understanding of the microstructure and phase composition of the coating, we evaluated the titanium and carbon content in the steel matrix and the volume content of carbide inclusions in the surfaced coating. Based on weighing the flux-cored and tubular wires without powder filling, we determined the composite powder content in the wire to be 18.65 wt.%. With a titanium carbide weight content of 0.41 in the composite powder, the titanium carbide content is 7.62 wt.% (or 11.7 vol.%).

Such a titanium carbide content in the surfaced coating can be obtained if all carbon and titanium are converted into the carbide phase during crystallization of the surfacing bath. However, according to our X-ray diffraction analysis results, the surfaced coating contains 5.69 vol.% titanium carbide. Therefore, we can assume that the carbon and titanium released during dissolution of the remaining carbide (6.0 vol.%) transfer into the solid solution of the steel matrix. Converting the volume percentage (6.0%) into weight percentage, we obtain 3.84 wt.% *TiC*. The carbon and titanium weight content in the carbide is 20% and 80%, respectively. Thus, the carbon content in the matrix is 0.77 wt.% and the titanium content is 3.07 wt.%.

Hardness and wear resistance of surfaced coatings

Table 4 shows the results of hardness measurements and abrasive wear tests of the surfaced coatings. The conversion of the hardness value of the flux-cored wire surfaced coating presented in Table 4 to the *Rockwell* hardness scale gives a value of 58.3 units. This hardness value corresponds to the hardness of hardened 0.8C carbon tool steel after low-temperature tempering. Thus, thermal multi-pass cycles during flux-cored arc surfacing ensure the hardening of a steel matrix containing 0.77 wt.% carbon. Titanium in the steel matrix in an amount of 3.07 wt.% can also influence the properties of the surfaced coating. The extent of the titanium effect is unknown, since the titanium content in industrial high-alloy steels usually does not exceed 1 wt.% [28].

The coating surfaced using the tubular *0.08C-0.07Al* steel wire without powder filling has low hardness and wear resistance (Table 4). The use of the composite powder significantly increases the hardness and wear resistance of the surfaced coating. The main reason for the increased wear resistance is, apparently, the higher hardness of the steel matrix, rather than the carbide inclusions. The volume content of these inclusions (5.69 vol.%) is too low to significantly influence both the hardness and wear resistance of the surfaced coating.

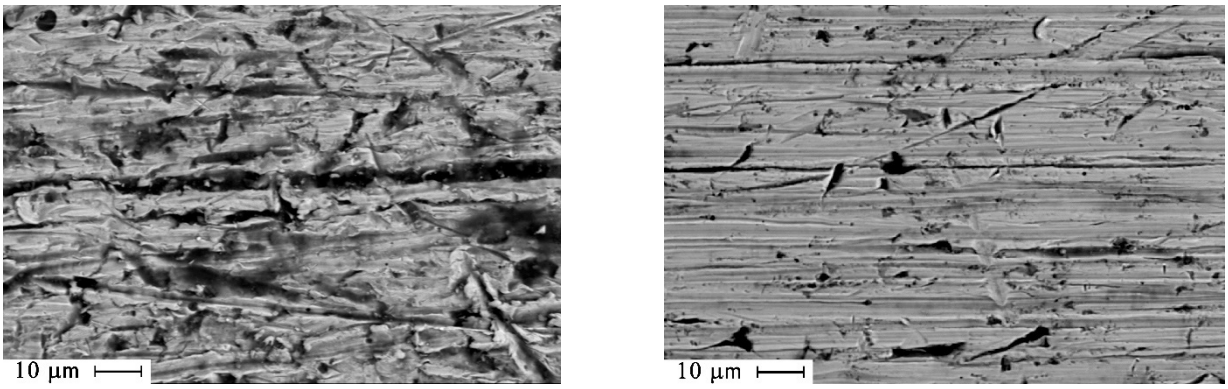
Table 4

Hardness and abrasive wear rate of the coatings

Surfacing	Microhardness (MPa)	Wear rate (mg/h)
tubular *0.08 C–Al* steel wire without powder filling	1,447 ± 53	387 ± 10
TiC + *α-Fe* flux-cored *0.08C-0.07Al* steel wire	6,629 ± 498	158 ± 11

Published results on the abrasive wear resistance of metal matrix composites show that the greatest positive effect is attained when the titanium carbide particles have a size of 20–30 μm and their volume content is about 50 vol.%. In this case, high wear resistance is provided by the uniformly distributed carbide particles in the matrix. These particles protect the metal matrix interlayers between carbide grains from abrasive wear. The abrasive wear resistance of the coating surfaced with *TiC* + *M2 HSS* (6% *W*, 5% *Mo*) composite powder (high-speed steel binder) increased 4.7-fold compared with the wear resistance of the coating surfaced with *M2 HSS* powder alone [29]. The corresponding increase in hardness does not exceed 20%, which confirms the critical role of the large carbide inclusions in increasing abrasive wear resistance. Similar results were obtained for electron beam coatings surfaced using "titanium carbide – titanium binder" composite powders [30]. After the addition of titanium carbide particles to the titanium matrix, the abrasive wear resistance increased 16-fold. At the same time, there is a 3-fold increase in hardness as well. We can assume that the main factor contributing to the increased wear resistance of titanium matrix composites is the presence of carbide inclusions in the metal matrix.

Fig. 7 shows images of the worn surfaces of the coatings. Based on the appearance of the surfaces, the wear mechanism for both deposited coatings is the same: micro-cutting by the sharp-angled corundum particles used for the abrasive wear tests. On the surface of the coating surfaced using tubular *0.08 C–Al* steel wire without powder filling, which has low hardness, the abrasive particles leave deep furrows, indicating a high wear rate. On the surface of the coating surfaced with the flux-cored wire, the abrasive particle tracks are much finer. In this case, the pressure of the abrasive particles pressed by the rubber roller is not sufficient to ensure their deep penetration into the hard surface of the deposited coating. Therefore, the wear rate of the coating surfaced using the flux-cored wire is several times lower than that of the coating surfaced using tubular *0.08C-0.07Al* steel wire without powder filling.



a *b*

Fig. 7. SEM images of worn surfaced surfaces:
a – tubular *0.08 C–Al* steel wire surfacing; *b* – *TiC* + **α**-*Fe* flux-cored *0.08 C–Al* steel wire surfacing

Conclusion

This study presents the results of the structure, hardness, and wear resistance of coatings obtained by flux-cored wire electric arc surfacing. The flux-cored wire was a thin-walled low-carbon steel shell filled with a granulated composite powder containing submicron titanium carbide and ferrite particles doped with silicon and aluminum. The composite powder was obtained by reaction synthesis in mechanically activated *FeTi35C5* ferrotitanium and carbon (carbon black) powder mixtures. The powder has an order of magnitude lower cost compared to powder mixtures of titanium carbide and steels used to produce flux-cored wires of similar composition. The Patent of the Russian Federation for the invention, No. 2750784, protects a technologically and economically efficient method for producing the composite powder.

During flux-cored electric arc surfacing, the carbide phase of the composite powder completely dissolves in the melt pool. Subsequently, carbon and titanium transfer into the liquid metal solution. During cooling of the melt pool, part of the carbon and titanium crystallizes as faceted titanium carbide inclusions with a volume fraction of **5.69 vol.%**, and the remaining carbon and titanium pass into the iron-based solid solution, forming a needle-like structure in the steel matrix.

The abrasive wear resistance of coatings obtained by flux-cored wire electric arc surfacing using the composite powder with submicron-sized carbide particles is primarily provided by the hardness of the steel matrix. The content of carbide particles in the structure of the surfaced coating is too low to significantly affect wear resistance and hardness. Therefore, the abrasive wear resistance of the coating appears to be similar to that of martensite-hardened steels.

A specific feature of the surfaced coating is the high titanium content dissolved in the α-*Fe* matrix. Further research is required to determine the possible beneficial effects of the abnormally high titanium content on the performance characteristics in order to clarify practical applications of the surfaced coatings.

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Conflicts of Interest

The authors declare no conflict of interest.