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FORMATION AND PROPERTIES OF NbC-REINFORCED LAYERS OBTAINED BY ELECTROSLAG SURFACING IN A SMALL-DIAMETER CURRENT-FED CRYSTALLIZER

The object of research is the process of forming NbC-reinforced composite layers by electroslag surfacing (ESS) in a small-diameter current-fed crystallizer (CFC). The problem being solved is the stable introduction of finely dispersed NbC into a small-diameter slag bath without dissolution and agglomeration, achieving uniform reinforcement, low porosity and high wear resistance.

The research is aimed at experimentally determining the microstructure, phase composition, hardness, porosity, and abrasive wear resistance of layers formed under controlled ESS conditions using powder wire containing 35 wt.% NbC, and justifying the technological feasibility of the process in small-diameter CFC.

The process was implemented in two-section CFC ∅ 65–85 mm under the following conditions: I = 1.1 kA; U = 22 V; feed rate V_{supply} = 2.0 m · min^{-1}; melting duration 45 s; T_{bath} = 1600–1700°C. Morphology and chemical homogeneity were determined by optical microscopy and SEM-EDS; phase composition – by X-ray diffraction; hardness – by Vickers HV10; abrasive wear resistance – according to ASTM G99.

Layers of 2.0 ± 0.2 mm without macro-cracks and slag inclusions were obtained, with a uniform distribution of NbC (≈ 2–5 μm) throughout the thickness. The average hardness is 1020 ± 30 HV10 (≈ × 3 compared to steel 20), the linear wear rate is reduced by 3.4 times, porosity is ≤ 0.8 vol.% while maintaining high adhesive strength. It has been confirmed that the controlled feeding of non-current-carrying powder wire into the most heated zone of the bath ensures reproducible transfer of the refractory phase and prevents its dissolution and coarsening. The agreed microstructural features correlate with an increase in hardness and a decrease in wear, confirming the cause-and-effect relationship "structure → properties".

The proposed technology can be implemented on existing ESS installations without re-equipment and is recommended for the restoration of parts operating under conditions of abrasive wear, with the potential for scaling up by regulating modes and controlling slag composition.

Keywords: *electroslag surfacing, carbide, niobium, composites, wear resistance, microstructure, hardness, porosity, tribotechnology, crystallizer.*

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1. Introduction

Electroslag surfacing (ESS) is an important technological process widely used to increase the wear resistance and strengthen the surfaces of various parts [1]. This method allows to effectively increase the service life of parts operating under conditions of increased abrasive wear, high temperatures and high mechanical loads [2]. One of the key tasks is to ensure a uniform distribution of refractory compounds in the metal matrix, which significantly affects the performance characteristics of the resulting composite layers. In particular, it is important to ensure the stability of the structure of refractory particles during the surfacing process and their uniform distribution in the metal [3].

Refractory compounds, such as carbides, nitrides, oxides, etc., play an important role in improving the properties of surfaced layers, including their hardness, abrasion resistance and overall wear resistance. High-quality carbides, such as niobium carbide (NbC), titanium carbide (TiC), tungsten carbide (W2C), are characterized by high strength and stability at high temperatures, which makes them suitable for use in ESS technologies [4]. However, an important aspect remains achieving the optimal combination of components in the charge to ensure maximum efficiency of the surfacing process and preservation of the structure of refractory particles in the metal [5].

Existing approaches to the use of refractory materials in ESS are largely based on the study of their influence on the mechanical properties of the resulting composite layers [6, 7]. The high-temperature properties of carbides allow significantly increasing the wear resistance of surfaced layers, as well as stabilizing their structure even under conditions of increased thermal load [8]. This study considers the use of niobium carbide for the formation of a composite layer, and also identifies the main parameters that affect the quality of the resulting materials [9].

A number of studies indicate the effectiveness of using refractory compounds to strengthen surfaces, especially under conditions of high mechanical loads and aggressive environments [10, 11]. For example, studies conducted by the authors confirm the feasibility of using flux-cored wires to obtain composite layers with a uniform distribution of refractory particles. The use of flux-cored wires with refractory materials allows to improve the quality of surfaced layers due to their ability to withstand high temperatures without structural destruction, which makes such layers extremely wear-resistant and stable [12]. The work shows that the introduction of refractory compounds into the slag bath is significantly complicated by the action of surface tension forces, which limits the possibility of their immersion in the slag. One way to overcome this problem is to use flux-cored wires, which allows to ensure uniform introduction of refractory particles into the slag bath and their effective distribution in the surfaced metal [13]. Studies confirm that the use of carbides, in particular niobium carbide (NbC), in the composition of flux-cored wires allows to achieve high hardness and wear resistance.

Also important is the issue of the stability of refractory compounds during the surfacing process. In works [14, 15], the behavior of various carbides during surfacing and their influence on the overall mechanical properties of the composite layer were investigated. In particular, it was found that the use of tungsten and titanium carbides allows to achieve a significant increase in hardness, but only niobium carbide provides simultaneous stability of the structure and increased wear resistance in aggressive conditions. In addition, the study notes the significant influence of the size of carbide particles on the uniformity of their distribution in the metal matrix, which is critically important for ensuring a long service life of surfacing surfaces [16].

In scientific sources, the issues related to the stable introduction of finely dispersed niobium carbide particles into a small-diameter slag bath without dissolution and agglomeration, the determination of optimal flux-cored wire feeding modes for uniform distribution of refractory particles in the layer, as well as the achievement of low porosity, high adhesive strength and stable hardness and wear resistance indicators [17]. In the course of the study, these issues were considered experimentally and confirmed by the results obtained.

Thus, the analysis of literary sources indicates the prospects of using niobium carbide for surfacing in conditions of high temperatures and aggressive abrasive environments [18]. The use of flux-cored wires with niobium carbide allows not only to increase wear resistance, but also to ensure the stability of the structure of composite layers during long-term operation.

The aim of research is to experimentally substantiate the approaches and tested parameters of electroslag surfacing using a flux-cored wire with 35 wt.% NbC for the formation of wear-resistant composite layers in small-diameter two-section current-fed crystallizers (CFCs), as well as to determine the microstructure, phase composition, hardness, porosity and abrasive wear resistance of the layers within the tested regimes.

To achieve the set aim, it is necessary to perform the following tasks:

1. To establish the microstructural features and phase composition of composite layers formed by electroslag surfacing using a flux-cored wire containing NbC in small-diameter two-section CFCs.
2. To quantitatively evaluate the operationally significant properties of the obtained layers – hardness (HV10), porosity and abrasive wear resistance (according to ASTM G99) – within the tested regimes.
3. To identify the relationships between the microstructure/phase composition and properties (hardness, porosity, wear resistance) of composite layers.
4. To summarize the results obtained and provide practically-oriented recommendations for the application of the process within the tested regimes and to confirm the technological capability of the process within the tested parameters.

2. Materials and Methods

The object of research is the process of forming NbC-reinforced composite layers by electroslag surfacing in a small-diameter CFC.

The subject of research is the microstructure, phase composition, hardness, porosity and wear resistance of the formed layers.

The surfacing was performed with a flux-cored wire with a diameter of 2.8 mm containing 35 wt.% niobium carbide. The process was implemented in two-section current-carrying crystallizers (∅ 65–85 mm) with the introduction of a non-conductive flux-cored wire into the slag bath using a PSh-107V semi-automatic welding machine (Ovruch plant "Pryladobudivnyk", Ukraine). The A-550 apparatus (Kakhovka Electric Welding Equipment Plant, Ukraine; developed by Paton Electric Welding Plant) and a special guiding device were used to stabilize the trajectory and depth of wire immersion in the most heated zone near the wall of the CFC section [19, 20].

ESS modes:

– current I = 1.1 kA;
– voltage U = 22 V;
– wire feed speed V = 2.0 m · min^{-1} (in the studies, it was varied from 1.5 to 3.0 m · min^{-1});
– duration of melting of one portion of metal – 45 s;
– the temperature of the slag bath was maintained at 1600–1700°C.

Layers with a thickness of 2.0 ± 0.2 mm were formed. The morphology and chemical homogeneity were examined using an optical microscope and a scanning electron microscope (SEM-EDS); the phase composition was determined by X-ray diffraction.

Microhardness was assessed by the Vickers HV10 method (n = 10) with the construction of profiles along the layer thickness. Abrasive tests were carried out in accordance with the ASTM G99 standard [21], (load 20 N, path length 500 m, counterbody – steel 45 HRC); the linear wear rate was calculated.

The following scientific methods were used in the work: analytical – to justify the choice of NbC as a reinforcing phase and the parameters of the ESS in small-diameter CFC; classification – to compare refractory compounds (borides, carbides, nitrides, oxides) by density and suitability for introduction into the slag bath; experimental – to plan a series of surfacings with varying feed rate and wire immersion depth; microstructural analysis – to quantify the size (2–5 μm) and distribution of NbC inclusions; mechanical tests – to determine HV10 and abrasive wear resistance; statistical processing of results – to calculate mean values, standard deviations and 95% confidence intervals of key indicators.

A flux-cored wire containing niobium carbide (NbC) was manufactured and investigated. The wire charge contained niobium carbide (NbC). To ensure the stability of the surfacing process and achieve optimal input parameters, a special wire feeding mechanism was developed using a PSh-107V semi-automatic welding machine.

The temperature of the slag bath was maintained at 1600–1700°C to ensure melting of the low-melting part of the charge and rapid transfer of the refractory component to the metal bath [22]. The composition of the flux-cored wire charge included 30–40% carbides (NbC, TiC, W_2C) and 60–70% low-melting matrix, which provided an optimal combination for a stable surfacing process.

To justify the choice of the reinforcing phase and the conditions for its introduction into the slag bath, comparative values of the density of typical refractory compounds (borides, carbides, nitrides, silicides, oxides) are given. The density parameter is critical for overcoming the effect of surface tension, immersion of particles in the melt and their uniform distribution in the surfaced layer, which directly affects the formation of the microstructure and wear-resistant properties [23].

The surfacing process was controlled by measuring the temperature of the slag bath and the flux-cored wire feed rate to ensure uniform distribution of refractory particles in the matrix [24]. Specially designed sensors allowed monitoring the temperature in different zones of the bath to avoid overheating or uneven heating [25].

Different wire feed parameters, such as feed rate (1.5–3.0 m/min) and wire immersion depth in the slag bath, were used for the experiments, which allowed assessing their influence on the formation of the composite layer. The optimal wire feed rate was set at 2.0 m/min, which ensures stable penetration and uniform distribution of carbides in the matrix. Fig. 1 shows the surfacing equipment before surfacing operations. It consists of the A-550 apparatus, a current-supplying crystallizer, a device for introducing flux-cored wire into the slag bath, and a wire feed mechanism.

Fig. 1. Surfacing equipment and devices prepared for surfacing with flux-cored wires

The supply of non-conductive filler wires to the slag bath, which is in a molten state due to the current-carrying section of the CFC, was carried out using the feed mechanism of the PSh-107V semi-automatic welding machine. To direct the end of the wire to the most heated zone of the slag bath (near the wall of the section), a guiding device was designed and manufactured. Fig. 2 shows the process of electroslag surfacing at the moment of introducing the flux-cored wire into the slag bath, and Fig. 3, 4 present the appearance of the resulting bimetallic workpiece and its transverse macrosection.

Fig. 2. The process of electroslag surfacing in a CFC at the moment of introducing the wire into the slag bath

Fig. 3. Appearance of the bimetallic workpiece

Fig. 4. Obtained sections of the surfaced workpiece

To evaluate the obtained composite layers, the methods of microgrinding and microhardness testing were used. Microgrinding was performed to determine the structure of the layer and the distribution of refractory particles, and microhardness testing was performed to determine the local hardness in different parts of the layer.

3. Results and Discussion

Within the framework of proven approaches and modes of electroslag surfacing (ESS) in a small-diameter current-fed crystallizer (CFC), a controlled scheme for introducing a flux-cored wire with niobium carbide (NbC) into the most heated zone of the slag bath was implemented in order to ensure uniform layer reinforcement, low porosity, and reproducible mechanical characteristics. The process was carried out in two-section CFCs ∅ 65–85 mm with flux-cored wire ∅ 2.8 mm and a content of 35 wt.% NbC, which was supplied as non-conductive using a PSh-107V semi-automatic machine, in conjunction with the A-550 apparatus and a special guiding device based on a semi-automatic welding machine to stabilize the trajectory and depth of immersion of the wire near the wall of the CFC section. Typical modes were: I = 1.1 kA; U = 22 V; V_{pod} = 2.0 m · min^{-1} (varied 1.5–3.0 m · min^{-1}); duration of penetration 45 s; t_{bath} = 1600–1700°C. Under these conditions, composite layers of 2.0 ± 0.2 mm were formed without macrocracks and slag inclusions, with a uniform distribution of NbC particles (≈ 2–5 μm) in thickness. This configuration of the equipment and modes provides control of the wire entry point, stabilization of the thermal field in the bath and control of the mass transfer of the refractory phase, which is crucial for the industrial reproduction of the technology in small-diameter CFC.

Experimental series showed that under the above modes, NbC particles were preserved in the structure of the surfaced metal without signs of decomposition, were distributed evenly (≈ 2–5 μm), and macrodefects were not recorded. The obtained average hardness of 1020 ± 30 HV10 (confirmed by a sample of n = 10) and a 3.4-fold reduction in linear wear rate relative to the base steel indicate the stability of the reinforcement and the efficiency of the transfer of the refractory phase in a small-diameter bath. Porosity ≤ 0.8 vol.% and visually confirmed absence of slag inclusions correlate with a controlled wire entry point and local thermohydrodynamics near the CFC wall, which minimizes agglomeration and promotes reproducible formation of a 2.0 ± 0.2 mm layer. The totality of these results confirms the operability of the proposed technological scheme for parts operating in abrasive conditions.

Electroslag surfacing was performed in two-section CFCs ∅ 65–85 mm with the supply of flux-cored wires ∅ 2.2–3.6 mm into the slag bath, which contained various solid components in the charge: carbides, oxides, nitrides, etc. Density of refractory compounds promising for use during ESS in CFCs.

Experimental data showed that niobium carbide did not decompose and remained in the structure of the surfaced metal, providing the necessary strength and wear resistance of the composite layer.

Table 1 shows the density of various refractory compounds that are promising for use during electroslag surfacing (ESS) [26, 27]. These compounds include borides, carbides, nitrides, silicides and oxides. The density of each compound is given in grams per cubic centimeter (g/cm³), which allows us to evaluate their properties from the point of view of their application for strengthening composite layers.

Fig. 5 shows the microstructure of the niobium carbide surfacing, the metallographic image clearly shows the presence of modifying niobium carbide impurities, which are preserved in the surfacing metal.

It was found that during surfacing with niobium carbide, composite layers with high hardness and wear resistance are formed. A comparison of different refractory compounds showed that the density of most of them exceeds the density of slag melts, which makes it difficult to introduce them into the slag bath. However, the use of flux-cored wires made it possible to achieve a more uniform distribution of refractory particles by optimizing their introduction rate.

Table 1

Physicochemical characteristics of refractory compounds promising for use in electroslag surfacing [26, 27]

Refractory compound	Composition of refractory compound	Density, g/cm^3
Borides	TiB	5.1
	TiB_2	4.5
	NbB	7.6
	NbB_2	7.0
	Cr_2B	6.1
	CrB_2	5.6
	ZrB_2	5.8
	B_4C	2.5
Carbides	SiC	3.2
	V_2C	6.0
	W_2C	17.1
	Nb_2C	7.8
	Cr_7C_3	7.0
	Cr_3C_2	7.0
	TiC	4.9
Nitrides	TiN	5.4
	ZrN	7.1
	NbN	8.3
	BN	3.5
	AlN	3.1
Silicides	FeSi	6.1
	B_6Si	2.1
Oxides	SiO_2	2.6
	Al_2O_3	3.9
	ZrO_2	5.6

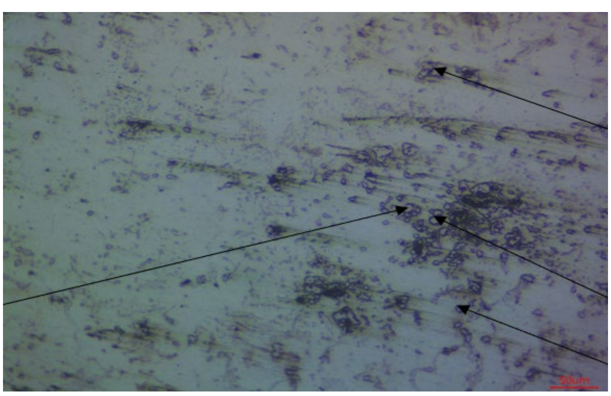

Fig. 5. Microstructure of the surfacing with niobium carbide (× 200) (black arrows indicate the inclusion of niobium carbide)

The results also indicate the stability of the surfacing process when using a wire with niobium carbide: carbide particles remained in the structure of the surfacing layer without signs of decomposition or destruction. This is confirmed by a micrograph, which clearly shows a uniform distribution of refractory particles in the matrix of the surfacing metal. This provided increased wear resistance of the composite layer, which makes the ESS technology promising for use in parts that are exposed to intense abrasive action.

Table 2 contains the results of mechanical tests of the obtained composite layers, where high hardness and abrasion resistance are noted compared to traditional materials. These results demonstrate the advantages of using refractory compounds to improve the performance of parts in severe operating conditions.

Table 2

Mechanical characteristics of composite layers with niobium carbide

Parameter	Value
Hardness (HV)	1020 ± 30
Abrasion resistance	High
Penetration depth	1.5–2.0 mm
Wear resistance	Increased

To quantify the reproducibility and dispersion of the results, the following statistical indicators of the tests are presented: sample size (n), means, standard deviations (σ) and 95% confidence intervals (CI) for the hardness HV10 and the wear coefficient K. These data refine the generalized results and confirm the stability of the obtained layer properties.

Detailed statistical characteristics for the hardness HV10 and the wear coefficient K are given in Table 3.

Table 3

Statistical indicators of mechanical tests (HV10; K)

Parameter	n	Average value	σ	95% CI
Hardness HV10	1 020 ± 30	1 020	30	± 19
Wear coefficient K ($mm^3 \cdot N^{-1} \cdot m^{-1}$)	5	$2.5 \cdot 10^{-4}$	$0.3 \cdot 10^{-4}$	$\pm 0.2 \cdot 10^{-4}$

The obtained data confirm that the use of niobium carbide in the flux cored wires allows to achieve high wear resistance and strength of the surfaced composite layers, which makes this technology effective for strengthening parts that are operated in aggressive conditions.

The use of refractory compounds in the flux cored wires opens up wide opportunities for increasing the service life of parts operating in the mode of hard abrasive and impact-abrasive wear (cultivator paws, plowshares, disk harrows, etc.). At the micro- and micro-level, the behavior of solid particles in the slag bath is determined not only by density gradients, but primarily by a complex of interphase phenomena:

– surface tension forces (γ) create an energy barrier that holds the refractory particle at the phase boundary "slag-gas" or "slag-blast";
– the wetting angle (θ) depends on the content of SiO_2, Al_2O_3, CaF_2 and alkaline earth metal oxides in the slag; increasing the basicity ($CaO/SiO_2 > 1.2$) and introducing fluorine reduce θ and facilitate the immersion of NbC, TiC or WC;
– the temperature gradient in the surface layers of the slag affects the viscosity and, accordingly, the speed of particle movement; the lower the local viscosity, the shorter the residence time on the surface;
– magnetohydrodynamic (MHD) forces at high currents (> 1.0 kA) generate circulating flows that can both promote immersion (intensive mixing) and push out lighter or hydrophobic particles.

It has been experimentally established that overcoming surface tension forces is achieved when the total mass of particles that are simultaneously in contact with the melt exceeds a certain critical threshold m, proportional to $(\gamma d^2)/\Delta\rho$ (where d is the average particle size, $\Delta\rho$ is the difference in densities of the "particle-slag bath"). For NbC particles with a diameter of 4–6 μm at a temperature of 1650°C, the critical mass is ≈ 0.4 g per 1 cm^2 of the bath surface.

Research limitations: The conclusions obtained relate to the system "steel 20 → layer 2.0 ± 0.2 mm → small diameter CFC (< 100 mm) → → flux-cored wire ∅ 2.8 mm with 35 wt% NbC → modes I = 1.1 kA;

U = 22 V; V = 2.0 m · min^{-1}". Other steel grades, other layer thicknesses, other SPC diameters, other NbC content or other particle size (beyond 2–5 μm) were not investigated. Tribological tests were performed according to the ASTM G99 scheme (20 N; 500 m; counterbody – steel 45 HRC), therefore impact-abrasive, corrosion-abrasive and wet environments were not covered. The composition of the slag and the "windows" of control of surface phenomena were not systematically varied. Statistical sampling for hardness (n = 10) and wear is limited at this stage.

Conditions for practical implementation: For industrial application, the following are required: technological regulations with tolerance fields (I, U, V, immersion depth, temperature 1600–1700°C); control of the composition/basicity of the slag and calibration of temperature sensors; instructions for wire feeding (PSh-107V) and trajectory settings; confirmation of adhesion strength by standardized tests; testing on target parts in production conditions; economic assessment of the cost of wires and downtime; requirements for labor protection and electrical safety.

The process is implemented in two-section current-carrying molds of small diameter (∅ 65–85 mm) using flux-cored wire containing 35 wt.% NbC. The generalized scheme includes the stages:

- preparation of the mold and workpiece;
- formation of a molten slag bath;
- controlled supply of wire with NbC to the surfacing zone;
- stabilization of the thermal regime;
- formation of a composite layer;
- control of cooling and flux removal.

Based on the results obtained, it is recommended to use the above approaches and parameters for the formation of wear-resistant layers in small-diameter CFC; the detailing of the mode selection should be carried out taking into account the requirements for the properties of the layer, the geometry of the mold and the conditions of specific production.

Further research: it is advisable to vary the NbC content in the flux-cored wire charge in the range of 30–40%, study the effect of slag composition on surface tension and wetting, comparative tests of NbC, TiC, and WC under identical conditions, as well as expand tribotests to impact and corrosion-abrasive conditions and scale up the process for other steel grades and layer thicknesses.

4. Conclusions

1. The technological capability of the process is confirmed: a composite layer with a controlled NbC particle size and morphology is stably formed in a small-diameter CFC, without critical defects. Consistent macro- and microstructural features indicate the reproducibility of layer formation and the suitability of the approach for scaling. Layers of 2.0 ± 0.2 mm were formed without macrocracks and slag inclusions at a porosity of ≤ 0.8 vol.%.

2. A balanced combination of properties was achieved: a decrease in porosity is accompanied by an increase in microhardness and a noticeable improvement in wear resistance without loss of layer integrity. The average hardness is 1020 ± 30 HV10 (n = 10), the linear wear rate is reduced by 3.4 times compared to steel 20.

3. The cause-effect relationship is substantiated: uniform distribution and favorable morphology of NbC reduce local stress concentrations and stabilize the tribopair. The reinforced matrix provides load transfer and resistance to micro-leaching. It is this configuration of the structure that determines the obtained increase in operational characteristics. The uniform distribution of NbC particles (≈ 2–5 μm) confirms the cause-and-effect relationship "structure → properties".

4. Applied technical guidelines for production have been formed: rational ranges of process parameters and quality control regulations compatible with typical equipment have been outlined; the transfer from the laboratory to pilot-industrial tests is justified and low-risk. Further optimization is advisable for specific load profiles and resource requirements of the customer.

Conflict of interest

The authors declare that they have no conflict of interest regarding this research, including financial, personal, authorship or other nature, which could affect the research and its results presented in this article.

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Use of artificial intelligence

The authors confirm that they did not use artificial intelligence technologies in creating the presented work.

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