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B.K. Rakhadilov[1,2], D.B. Buitkenov[3], A.K. Apsezhanova[2]✉,
N.M. Magazov[2], M.B. Bayandinova[2]

[1]*PlasmaScience LLP, Ust-Kamenogorsk, Kazakhstan;*
[2]*D. Serikbayev East Kazakhstan Technical University, Ust-Kamenogorsk, Kazakhstan;*
[3]*S. Amanzholov East Kazakhstan University, Ust-Kamenogorsk, Kazakhstan*

Influence of Wire Type on the Structure and Properties of Coatings Obtained by Electric Arc Metallization

Electric arc metallization (EAM) is one of the most effective and widely used thermal spraying methods, in which a protective coating is formed by melting a metal wire with an electric arc and atomising the molten material with a stream of compressed air. This technology is characterised by high productivity, adjustable layer thickness, and the versatility of applicable materials. This study presents a comparative analysis of protective coatings applied to 65G steel using electric arc metallization with both powder and cast wires made of 30KhGSA and 51KhFA alloys. The microstructure of the coatings was examined using a scanning electron microscope, and the elemental composition was determined using energy dispersive spectroscopy (EDS). The thickness and porosity of the coating were evaluated using an optical microscope. Microhardness was measured using Vickers, and surface roughness was evaluated using contact profilometry. Microstructural and EDS analyses revealed that coatings produced with cored wires exhibit a more homogeneous distribution of alloying elements, resulting in improved microhardness, reduced porosity. In contrast, coatings obtained with cast wires showed structural inhomogeneity, leading to increased porosity and decreased mechanical performance. Surface roughness measurements indicated that cored wire coatings had higher roughness values, particularly for 51KhFA. The findings analyzed that powder (cored) wire offers superior coating quality.

Keywords: electric arc metallization, cast and powder wire, porosity, steel coating, elemental composition

✉*Corresponding author*: Apsezhanova Akbota, akbotaapsezanova@mail.com

Introduction

Under the operating conditions of agricultural machinery in Kazakhstan, where machine components are subjected to intense abrasive wear, the task of improving the wear resistance of working elements is of particular relevance. One of the promising solutions is the formation of protective layers using the electric arc metallization (EAM) method, which enhances wear resistance and extends the service life of components [1].

Electric arc metallization (EAM) is one of the most effective and widely used thermal spraying methods, in which a protective coating is formed by melting a metal wire with an electric arc and atomising the molten material with a stream of compressed air [2]. This technology is characterised by high productivity, adjustable layer thickness, and the versatility of applicable materials, making it particularly relevant in mechanical engineering, aviation, shipbuilding, and the oil and gas industries [3, 4]. The process involves the formation of an arc between two wire electrodes, causing the metal to melt and be deposited onto a pre-prepared surface in the form of fine particles.

One of the key factors determining the structure and operational characteristics of coatings obtained by EAM is the choice of wire material [5–7]. The wire used in the EAM process can be made in the form of a solid (cast) metal rod or in the form of a powder (tubular) shell filled with alloying or hardening powders. These differences in wire design directly affect the melting characteristics, melt transfer, microstructure formation, and, ultimately, the physical and mechanical properties of the protective layer [8].

Cast wire is a solid metal wire with a uniform chemical composition, suitable for rolling and drawing. However, its alloying capabilities are limited, which reduces the potential for optimizing the properties of the coating [9, 10]. In addition, the heterogeneity of melting during spraying can contribute to the formation of agglomerates, local areas with a deficiency of alloying elements and, as a result, increased porosity and impaired adhesion of the coating to the substrate [11–14]. Powder (tubular) wire, on the other hand, provides much greater flexibility in forming the required composition [15, 16]. A metal shell filled with a powder mixture of elements and compounds (including carbides, borides, oxides, etc.) allows coatings with specially specified properties to be obtained, including increased hardness, wear resistance, and corrosion resistance [17–19]. The use of powder wires is particularly effective when it is necessary to use difficult-to-form alloying systems that are not suitable for the manufacture of cast wire.

The chemical composition of the wire plays a decisive role in the formation of the coating structure. Alloying elements influence the formation of carbide, boride, and intermetallic phases, which increase hardness, wear resistance, and resistance to stress corrosion cracking. However, to achieve the positive effect of alloying, it is important not only to have the nominal concentration of elements, but also their uniform distribution throughout the coating. With EAM, coatings obtained from cast wire often show zoning and uneven distribution of elements, while tubular wire allows for greater chemical uniformity, which is directly related to improved microhardness, density, and adhesion properties [7].

This study presents a comparative analysis of protective coatings applied to 65G steel using electric arc metallization with both powder and cast wires made of 30KhGSA and 51KhFA alloys. The scientific novelty of this work lies in the fact that, for the first time, a systematic and direct comparative analysis was conducted between cast and powder-filled wires of the same steel grades (30KhGSA and 51KhFA) in terms of their influence on coating structure and performance. The findings are particularly relevant for improving the durability of components used in the harsh, abrasive conditions of Kazakhstan's agricultural environment.

Materials and methods

65G steel, a high-carbon steel characterized by high hardness and wear resistance, was used as the substrate material for spraying. It is widely used in the manufacture of parts operating under conditions of increased loads and wear, such as cultivator tines, plow blades, and other agricultural machinery components. The chemical composition of the material is presented in Table 1.

Table 1

Chemical composition of 65G steel substrate, %

Element	C	Si	Mn	Ni	S	P	Cr	Cu	Fe
Content	0.62–0.70	0.17–0.37	0.9–1.2	≤0.25	≤0.035	≤0.035	≤0.25	≤0.20	basis

The substrate samples were cut from sheet metal measuring 25×10×4 mm. The surface was mechanically sanded (grain size from P100 to P360) and sandblasted with electrocorundum to create the required roughness and improve coating adhesion.

Steel wires with a diameter of 1.6 mm of two types—cast and cored—were used as the feedstock material for thermal spraying. The chemical composition of the wires corresponds to the steel grades 30KhGSA and 51KhFA. The selection of wires was based on differences in alloying composition. Detailed chemical composition data are presented in Table 2. For each composition, both cast and cored wire types were utilized. The wires were procured in ready-made form.

Cast wires were produced using the conventional method of metal melting followed by forming, whereas cored wires consisted of composite fillers enclosed in a metallic sheath. Figure 1 illustrates the elemental distribution in the composition of the 51KhFA wire used in this study. This selection enabled an objective comparative analysis of the influence of wire type and chemical composition on the structure and performance properties of the resulting coatings.

Table 2

Main grades and chemical composition of sprayed wires, %

Wire name	Fe %	C %	Si %	Mn %	Ni %	S %	P %	Cr %	Cu %	Mo %	As %
30KhGSA	basis	0.28–0.34	0.9–1.2	0.8–1.1	to 0.3	to 0.025	to 0.025	0.8–1.1	to 0.3	–	–
51KhFA	basis	0.47–0.55	0.15–0.3	0.3–0.6	to 0.25	to 0.025	to 0.025	0.75–1.1	to 0.2	–	–

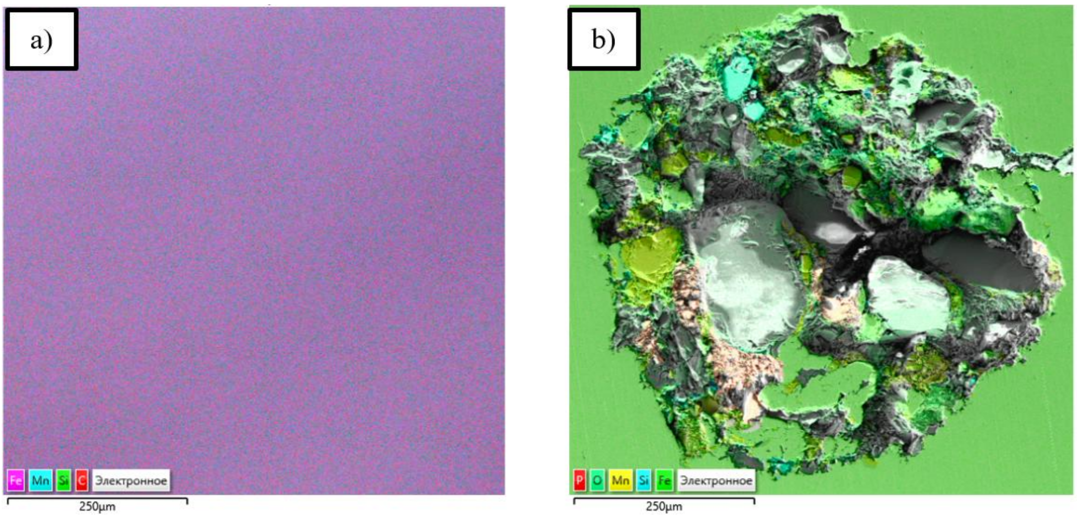


Figure 1. Cross-sectional view and distribution of elements in cast (*a*) and powder (*b*) 51KhFA wires

Electric arc metallization was carried out on a supersonic arc metallization unit SX-600, which included the following main components: a sprayer, a power source, and a compressor. The process was carried out under the following technological parameters: the power source voltage was 40 V, which ensured the stability of the electric arc and sufficient energy for melting the material. The current was set at 250 A. The wire feed rate was maintained at 12 cm/s, which ensured a stable supply of material and uniformity of the applied layer. The distance between the sprayer and the sample surface was 200 mm, which allowed for uniform distribution of the melt and reduced the thermal impact on the substrate. The working gas (compressed air) pressure was maintained at 0.7 MPa, ensuring effective particle acceleration and the formation of a dense coating structure [10]. Spraying was carried out at room temperature for both the samples and the environment, which minimized thermal impact and maintained the stability of the material structure.

Table 3

Electric arc metallization modes

Parameter	Value
Voltage (U), B	40
Current (I), A	250
Wire feed speed, cm/s	12
Distance from nozzle, mm	200
Compressed air pressure, MPa	0.7
Ambient temperature, °C	26

For a comparative analysis of coatings deposited by electric arc metallization using different wires, modern methods were used to study their structural and phase composition, microstructure, and mechanical properties [11].

The microstructure of the coatings was studied using a Tescan Vega 4 scanning electron microscope. The elemental composition was determined using Xplore 30 energy dispersive analysis. The thickness and porosity of the coatings were measured using an Olympus BX53M optical microscope, and the porosity was calculated using Metallographic Analysis Software in accordance with ASTM E2109. Microhardness was measured using the Vickers method (GOST 9450-76, ASTM E384-11) at a load of 0.025 N. Surface roughness was evaluated using a model 130 profilometer (GOST 25142-82).

Results and discussion

Figure 2 shows the typical microstructure of 30KhGSA wire obtained using scanning electron microscopy (SEM). This microstructure is typical for coatings obtained by electric arc metallization. Microstructural analysis showed that coatings formed by electric arc metallization have a characteristic layered (lamellar) structure. This morphology is typical for thermally sprayed coatings and is formed as a result of the sequential deposition of molten metal particles. During spraying, the particles, upon reaching the substrate surface, instantly cool and solidify, forming dense and thin layers. Rapid cooling caused by the contact of hot particles with a cold base or previously applied layers leads to instant crystallization and contributes to the formation of a strong, homogeneous microstructure. This structure ensures reliable adhesion between layers due to partial thermal fusion at the melt boundaries. The lamellar structure significantly increases the mechanical strength of the coating, its resistance to cracking and abrasive wear, and reduces permeability to moisture and aggressive environments. Thus, the microstructure shown in Figure 1 indicates the high quality of the coating and confirms the effectiveness of the technological parameters used to form reliable protective coatings based on 30KhGSA wire.

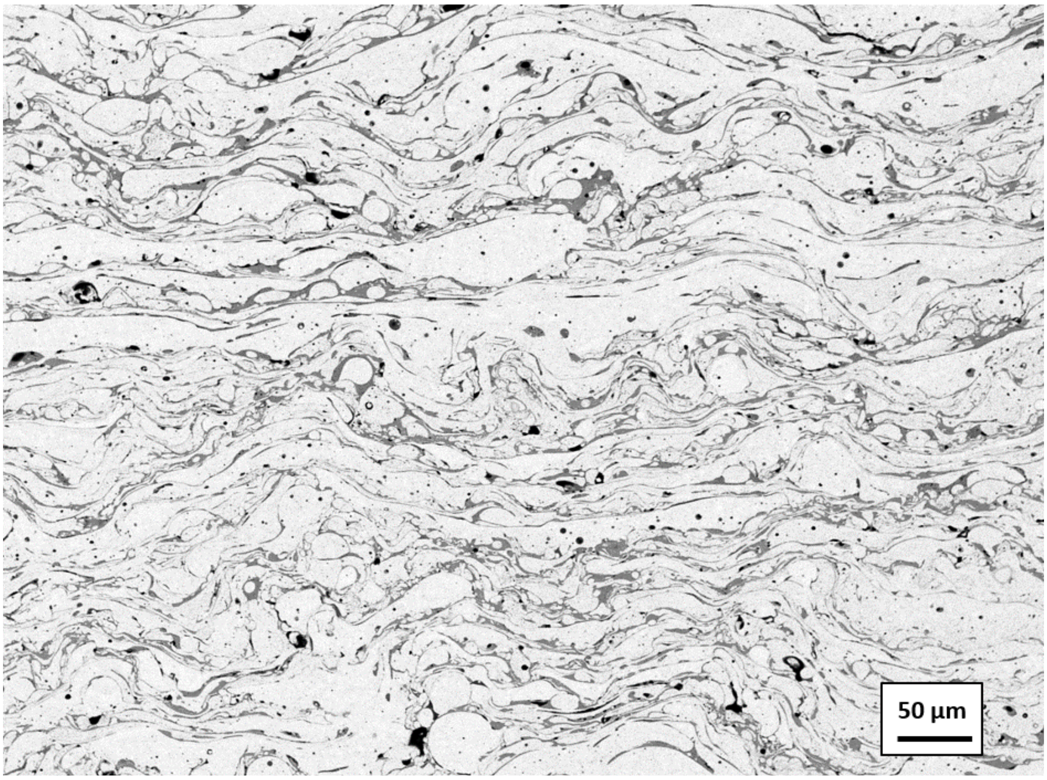
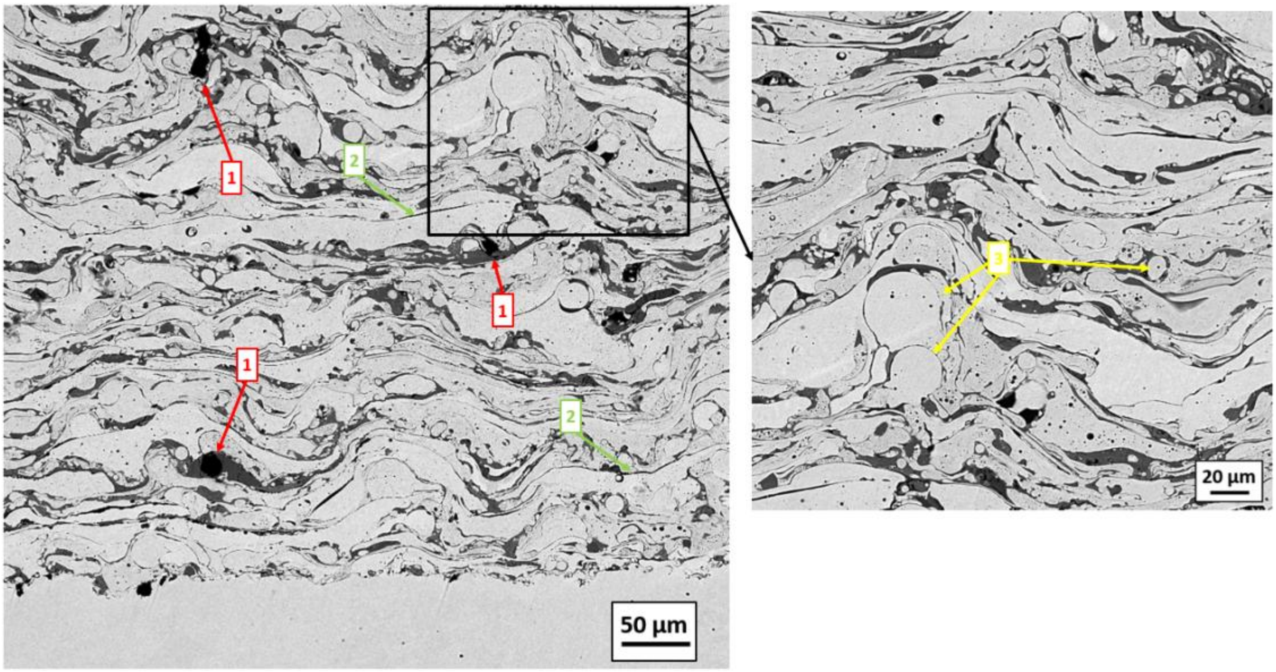


Figure 2. Layered microstructure of the coating cross section

However, characteristic defects were also identified in the coating structure, including pores, delaminations, and unmelted particles (Fig. 3), the presence of which can significantly affect the performance characteristics of the coatings. Pores typically formed due to air entrapment during spraying or incomplete sintering of the sprayed particles, especially when the particle temperature or velocity is insufficient. These porous regions may serve as pathways for the ingress of aggressive media, promoting corrosion and reducing the sealing properties of the coating [13].

Delaminations were mainly observed at interlayer boundaries and at the coating—substrate interface. Their presence may indicate violations in the surface pre-treatment process (e.g., inadequate cleaning or insufficient surface roughness), as well as insufficient kinetic energy of the sprayed particles, which fails to ensure reliable adhesion to the substrate. Such defects significantly reduce coating adhesion and may lead to its premature failure under mechanical loading.

Unmelted particles present in the structure are typically fragments of wire that did not fully melt during the arc metallization process. These inclusions can act as stress concentrators and potential initiation sites for microcracks. Under abrasive or impact loads, they contribute to accelerated wear of the coating, reducing its strength, hardness, and resistance to failure.



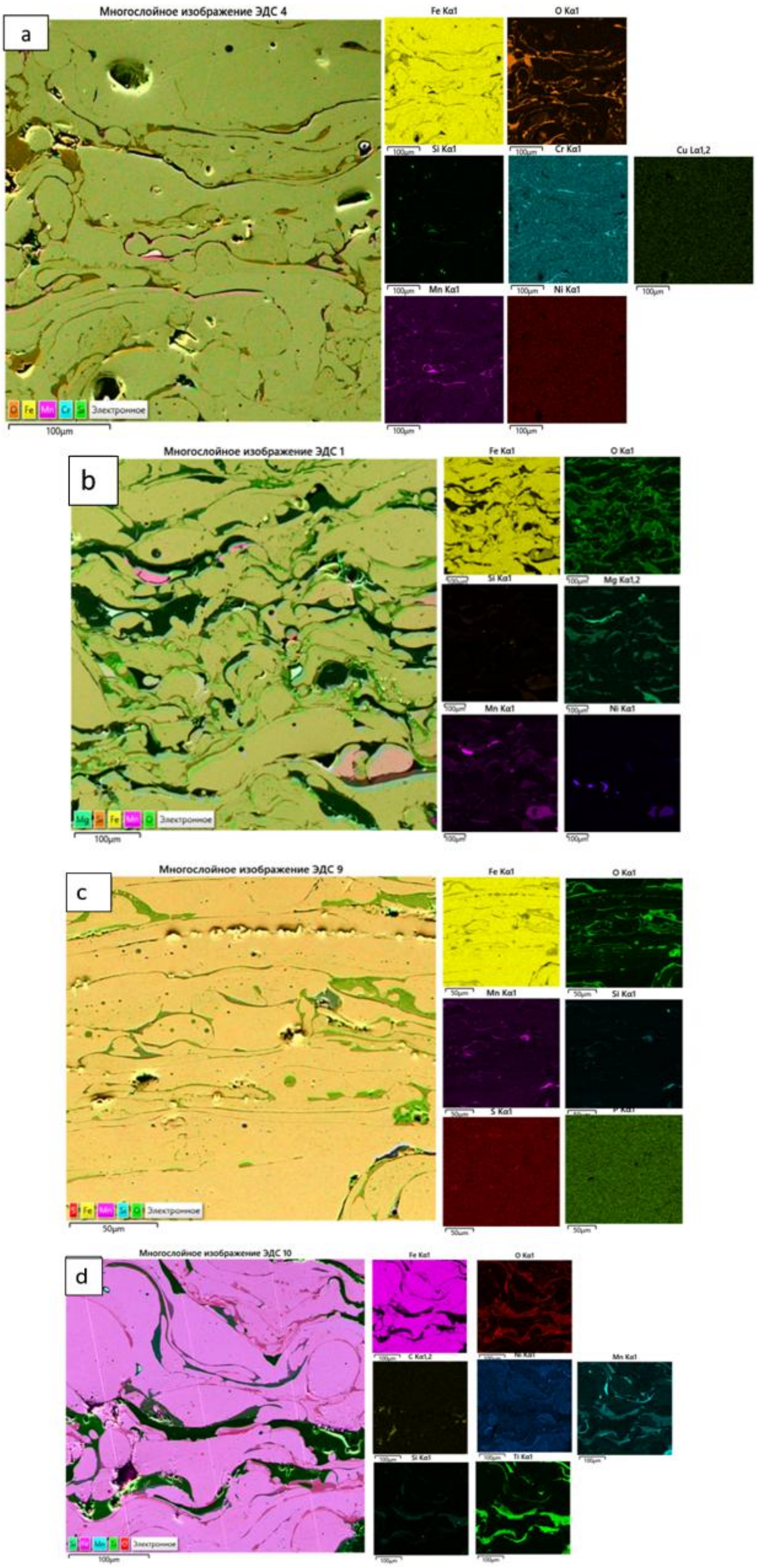
1 — pores; *2* — delamination; *3* — unmelted particles

Figure 3. Microstructural analysis of the coating with identification of defect areas in the form of pores, delamination, and unfused particles

To gain a deeper understanding of the influence of wire type on the chemical distribution within the coating, EDS analysis was performed on cross-sections of samples produced using both cored and cast wires of 30KhGSA and 51KhFA (Fig. 4). The results of EDS mapping for elements Fe, O, Si, and Mn help explain the observed differences in microstructure and, consequently, in the performance characteristics of the coatings. Coatings obtained from cored wires of 30KhGSA and 51KhFA exhibit relatively uniform distribution of alloying elements (Fig. 4*b*–*d*); however, the 30KhGSA coating shows a slightly coarser and more heterogeneous distribution pattern, whereas the 51KhFA coating demonstrates a more stable and homogeneous profile.

This partial distinction is reflected in the functional properties: both coatings are characterized by high microhardness (up to 720 HV), low porosity (4.3–5.0 %), and good adhesion strength (up to 19.2 MPa), with the values for 51KhFA appearing slightly more balanced. In contrast, cast wires of 30KhGSA and 51KhFA exhibit pronounced chemical heterogeneity, including localized depletions, agglomerations and “hot spots”, indicating non-uniform delivery of alloying elements during spraying. This inhomogeneity results in the formation of structural defects—such as pores, voids, and delaminations—which is further supported by SEM images showing that void-rich regions coincide with Cr- or Si-depleted areas identified through EDS analysis. Thus, the chemical inhomogeneity characteristic of cast wires is directly linked to increased porosity (up to 8.2 %), reduced hardness, and weakened adhesion to the substrate, whereas the more uniform (albeit not perfectly smooth) elemental distribution in cored wires contributes to improved performance characteristics.

An analysis of the coating characteristics shows the influence of the type and composition of the wire on the operational characteristics (Table 4). Among the samples studied, powder wire, in particular 51KhFA and 30KhGSA, demonstrated clear advantages in terms of coating density and microstructure uniformity. Although cast wires produce slightly thicker layers, coatings applied using powder wires have lower porosity (4.3–5.0 %) and more favorable surface morphology. According to roughness data, powder 51KhFA showed higher roughness values, which may be due to particle distribution characteristics or localized defects, while cast wire demonstrated a smoother surface. However, in terms of mechanical strength, Vickers microhardness tests confirmed that powder wire coatings achieve higher hardness (up to 720 HV), especially powder 30KhGSA. These results confirm that, despite minor changes in roughness, powder wire provides superior coating quality in terms of structural integrity, hardness, and defect reduction, making it more suitable for applications requiring increased wear resistance.



a — 30KhGSA cast wire; *b* — 30KhGSA cored wire; *c* — 51KhFA cast wire; *d* — 51KhFA cored wire

Figure 4. EDS mapping of coating cross-sections obtained by arc metallization using different wire types

T a b l e 4

Comparison of key properties of coatings obtained using different types of wires

Wire	Thickness, μm	Porosity, %	Roughness Ra, μm	Microhardness, HV
30KhGSA (cored)	111.26	4.3	6.03	720
30KhGSA (cast)	158.92	7.8	6.02	620
51KhFA (cored)	160.84	5.0	7.9	700
51KhFA (cast)	148.83	8.2	6.1	650

In general, differences in the structure and properties of coatings are related to both the chemical composition and the method of wire production: powder wire technologies allow for precise dosing of components and uniform spraying, while cast wire often contains defects that disrupt the uniformity of the coating.

Conclusion

The studies conducted demonstrated a significant influence of the wire type on the quality of coatings obtained by the electric arc metallization method. It has been established that 30KhGSA and 51KhFA powder wires provide more uniform coatings with high microhardness (up to 720 HV), reduced porosity (4.3–5.0 %), and strong adhesion to the substrate (up to 19.2 MPa). This is due to the uniform distribution of alloying elements, confirmed by EDS mapping results, as well as the minimization of structural defects—pores, unfused inclusions, and delamination. At the same time, coatings applied using cast wire were characterized by higher porosity (up to 8.2 %), chemical and structural heterogeneity, and reduced adhesion, which reduces their performance characteristics.

Thus, powder wires with an optimal chemical composition have a significant advantage in the formation of steel coatings. The data obtained emphasize the importance of rational selection of wire material and process parameters. In the future, it is planned to expand the range of wire materials under investigation, optimize spraying modes using mathematical modeling methods, and test coatings under various types of wear conditions.

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Б.К. Рахадилов, Д.Б. Буйткенов, А.Қ. Әпсежанова, Н.М. Магазов, М.Б. Баяндинова

Электр доғалы металдандыру әдісімен алынған жабындардың құрылымы мен қасиеттеріне сым түрінің әсері

Электр доғалы металдандыру (ЭДМ) — бұл қорғаныш жабындарын алу үшін метал сымын электр доғасымен ерітіп, алынған балқыманы сығылған ауа ағынымен шашырату арқылы жүзеге асатын, кеңінен қолданылатын және тиімді термиялық бүрку әдістерінің бірі. Бұл технология жоғары өнімділікпен, қабат қалыңдығын реттеу мүмкіндігімен және қолданылатын материалдардың әмбебаптығымен ерекшеленеді. Мақалада 65Г болатқа 30ХГСА және 51ХФА қорытпаларынан жасалған ұнтақты және құйма сымдарды қолдану арқылы алынған жабындардың салыстырмалы талдауы ұсынылған. Жабынның микроқұрылымы сканерлік электронды микроскоппен зерттелді, ал элементтік құрамы энергодисперсиялық спектроскопия (EDS) әдісімен анықталды. Қаптаманың қалыңдығы мен кеуектілігі оптикалық микроскоппен өлшенді. Микроберіктік Виккерс әдісімен, ал беткі кедір-бұдырлық контактілі профилометрмен бағаланды. Микроқұрылым және EDS талдауы ұнтақты сыммен алынған жабындардың қоспалау элементтері біркелкі таралғанын, бұл өз кезегінде микроберіктікті арттырып, кеуектілікті азайтатынын көрсетті. Құйма сыммен алынған жабындарда құрылымдық біркелкі еместік байқалып, кеуектілік артты және механикалық қасиеттері нашарлады. Зерттеу нәтижелері ұнтақты сымның жоғары сапалы жабындар алудағы артықшылықтарын көрсетті.

Кілт сөздер: электр доғалы металдандыру, құйма және ұнтақ сымды, кеуектілік, болат жабын, элементтік құрам

Б.К. Рахадилов, Д.Б. Буйткенов, А.Қ. Әпсежанова, Н.М. Магазов, М.Б. Баяндинова

Влияние типа проволоки на структуру и свойства покрытий, полученных методом электродуговой металлизации

Электродуговая металлизация (ЭДМ) является одним из наиболее эффективных и широко применяемых методов термического напыления, при котором защитное покрытие формируется за счёт плавления металлической проволоки электрической дугой и распыления расплава сжатым воздухом. Технология отличается высокой производительностью, регулируемой толщиной слоя и универсальностью применяемых материалов. В статье представлена сравнительная оценка защитных покрытий, нанесённых на сталь 65Г методом дуговой металлизации с использованием порошковой и литой проволоки из сплавов 30ХГСА и 51ХФА. Микроструктура покрытий исследовалась с использованием сканирующего электронного микроскопа, а элементный состав — методом энергодисперсионной спектроскопии (EDS). Толщина и пористость покрытия определялись с помощью оптического микроскопа. Микротвёрдость измерялась по Виккерсу, шероховатость поверхности — с использованием контактного профилометра. Анализ микроструктуры и EDS показал, что покрытия, полученные из порошковой проволоки, характеризуются более равномерным распределением легирующих элементов, что обеспечивает повышенную твёрдость и снижает пористость. Покрытия из литой проволоки, напротив, демонстрируют структурную неоднородность, повышенную пористость и ухудшенные механические характеристики. Установлено, что порошковая проволока обеспечивает более высокое качество покрытий.

Ключевые слова: дуговая металлизация, литая и порошковая проволока, пористость, стальное покрытие, элементный состав

Information about the authors

Rakhadilov, Bauirzhan — Doctor of Philosophy (PhD) in Science, Associate professor, LLP "PlasmaScience", Leading Researcher, Ust-Kamenogorsk, Kazakhstan; e-mail: rakhadilovb@gmail.com, ORCID: https://orcid.org/0000-0001-5990-7123;

Buitkenov, Dastan — PhD, Leading Researcher of Scientific Research Center "Surface Engineering and Tribology", S. Amanzholov East Kazakhstan University, Ust-Kamenogorsk, Kazakhstan; e-mail: buitkenov@gmail.com; ORCID ID: https://orcid.org/0000-0002-0239-5849;

Apsezhanova, Akbota (*contact person*) — PhD student in the specialty 8D05301 — Technical Physics, D. Serikbayev East Kazakhstan Technical University (EKTU), Researcher at the Research Center "Protective and Functional Coatings", Ust-Kamenogorsk, Kazakhstan; e-mail: akbotaapsezanova@mail.com; ORCID: https://orcid.org/0009-0001-7778-7767

Magazov, Nurtoleu — PhD student in the specialty 8D05301 — Technical Physics, D. Serikbayev East Kazakhstan Technical University (EKTU), Researcher at the Research Center "Protective and Functional Coatings", Ust-Kamenogorsk, Kazakhstan; e-mail: magazovn@gmail.com; ORCID: https://orcid.org/0000-0002-9941-9199

Bayandinova, Moldir — PhD student in the specialty 8D05301 — Technical Physics, at S. Amanzholov East Kazakhstan University, Kazakhstan; e-mail: shohmanovamb@gmail.com, ORCID: https://orcid.org/0000-0001-6699-9097