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Zh.B. Sagdoldina[1,2], A.B. Leonidova[2*], A.Zh. Zhassulan[2,3], A.B. Shynarbek[3], Zh. Turar[4]
[1]Sarsen Amanzholov East Kazakhstan University,
070000, Kazakhstan, Ust-Kamenogorsk, 30 Gvardeiskoi Divizii Street, 34
[2]Shakarim University,
071412, Kazakhstan, Semey, Fizkulturnaya Street, 4
[3]Engineering Center, Shakarim University,
071412, Kazakhstan, Semey, Glinka Street, 20 A
[4]Sakarya University,
54050, Turkey. Sakarya, Akademiyolu Street, 5-20
*e-mail: aiymleonidova1994@gmail.com

MODERN APPROACHES TO THE MODIFICATION OF COATINGS PRODUCED BY ELECTRIC ARC SPRAYING (REVIEW)

Abstract: *In this review article, modern approaches to improving the performance characteristics of coatings produced by electric arc spraying are analyzed. Particular attention is given to studies in the field of directed energy deposition using an electric arc (DED-Arc), including the selection of spraying parameters, substrate surface preparation, and the application of new types of wires and composite materials. Advances in feedstock design for corrosion-resistant, heat-resistant, and wear-resistant protection are reviewed, including Zn, Al-Mg, and Zn-Al-Mg systems, Al-Cu cored wires for antifouling applications, stainless steel and NiCrMoAl alloys, cermets, and WC-reinforced high-entropy alloys. The review also summarizes recent results on adhesion enhancement through laser surface texturing and on adapting electric arc spraying technology for non-conductive substrates. Particular attention is given to the relationships between processing parameters, coating microstructure, and functional properties. The analysis highlights key factors controlling coating performance and identifies current research challenges in arc-sprayed coating systems. The summarized results demonstrate that electric arc spraying is a flexible and cost-effective technology for producing functional coatings with tailored properties for a wide range of industrial applications.*
Key words: *electric arc spraying; DED-Arc; coatings; adhesion; corrosion protection.*

Introduction

Under conditions of intensive service of structural materials, the demand for effective methods to enhance their durability and resistance to external influences is steadily increasing. One of the promising approaches in this field is the application of coatings produced by thermal spraying techniques, among which electric arc spraying (EAS) occupies a special position due to its technological simplicity, cost efficiency, and high productivity. However, despite the widespread use of EAS in various industrial sectors, a number of limitations remain related to the formation of coatings with optimal structural and performance characteristics.

In this regard, research efforts aimed at improving the electric arc spraying process have intensified, particularly through the introduction of new approaches to feedstock material selection and the modification of spraying parameters. The enhancement of coating performance properties is generally achieved through an integrated approach that includes the use of modern additive technologies, alternative wire materials, and methods for controlling coating structure at different stages of its formation.

This review is devoted to the analysis of existing and promising approaches to improving the performance characteristics of coatings produced by electric arc spraying. The presented analysis makes it possible to systematize the accumulated knowledge in this field and to identify relevant directions for further research.

DED-Arc Technology. Among the modern directions aimed at improving the quality and functionality of coatings produced by electric arc spraying, particular attention is given to directed energy deposition using an electric arc (DED-Arc). This approach combines the principles of additive manufacturing and welding processes, enabling the formation of volumetric structures and coatings with controlled geometry and properties.

Thus, in the study by R. M. Kindermann et al. [1], a comprehensive investigation was carried out to examine the influence of heat input and process interruptions on the microstructure and mechanical properties of the Inconel 718 alloy (Figure 1) fabricated by directed energy deposition using an electric arc (DED-Arc). Special attention in this study was paid to the effect of interruptions during the deposition process. The authors compared two deposition modes – Cold Metal Transfer (CMT) and pulsed Gas Metal Arc Welding (GMAW-P) – and demonstrated that controlling heat input and interpass temperature allows targeted control of the phase composition by regulating the amount of strengthening phases (γ′ and γ″), which is critically important for heat-resistant nickel-based alloys. The CMT mode provides lower heat input, which in turn reduces the risk of crack and pore formation and promotes increased ductility of the deposited samples. In contrast, the GMAW-P mode, despite increasing material strength due to more intensive formation of strengthening phases (γ′ and γ″), was accompanied by a higher tendency toward defect formation during solidification. It was shown that even short-term arc interruptions lead to the formation of thermally unstable zones with localized stresses, which significantly reduce tensile strength and promote material failure.

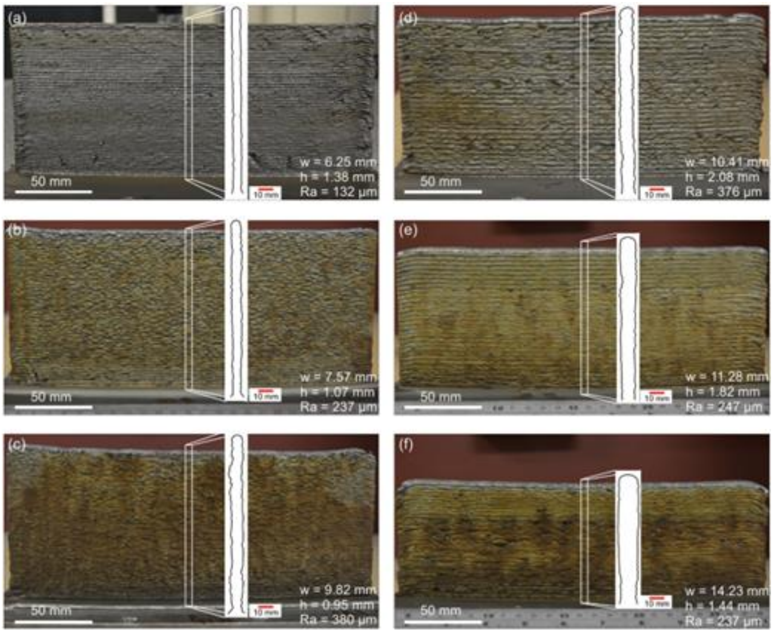

Figure 1 – DED-Arc IN718 specimens produced in this study: (a) CMT-1.0-80°C, (b) CMT-1.0-30 s, (c) GMAW-P-1.0-30 s, (d) CMT-0.4-80°C, (e) CMT-0.4-30 s, and (f) GMAW-P-0.4-30 s. Cross-sectional profiles: w = total wall width, h = layer height, Ra = average surface roughness [1]

A number of studies have reported a significant influence of DED-Arc process parameters on the morphology and quality of the formed surface. In particular, Hensel J. et al [2] demonstrated that the surface of components produced by DED-Arc exhibits both random and deterministic topographical features. The layer height and the number of deposition passes are formed in a predictable manner, whereas the occurrence of surface protrusions and excess deposited material is of a stochastic nature. Surface topography can be described using W-profiles, while height parameters can be obtained based on laser scanning (Figure 2). The authors emphasize that measurement parameters, such as cutoff wavelength, evaluation length, and profile length, have a significant effect on the calculated surface characteristics and must be explicitly reported in data analysis.

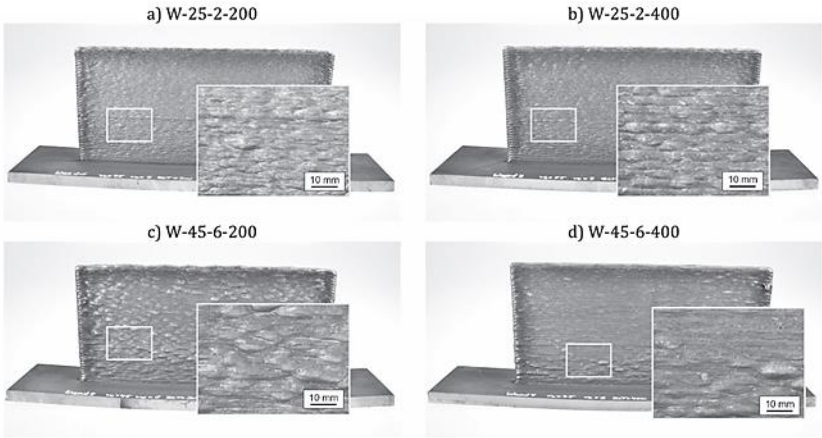

Figure 2 – Photographs of DED-Arc specimens produced under different welding parameters and interpass temperatures (a) and (d) [2]

The relevance of the DED-Arc process is confirmed not only by its high technological flexibility but also by the possibility of fine control over the structure and properties of the deposited material through the selection of deposition strategies. In the study by de Brito Neto F. M. et al. [3], the influence of different deposition strategies on the microstructure and mechanical property anisotropy of 316L stainless steel components fabricated by DED-Arc was investigated. The authors note that DED-Arc is characterized by a high deposition rate, cost efficiency, and low material waste, making it particularly effective for the fabrication of large-scale metal components with complex geometries. At the same time, a lack of fundamental studies related to the formation of thick-walled structures is highlighted. Within the framework of this study, it was shown that the choice of deposition strategy has a significant effect on crystallographic texture, phase morphology, and residual stress distribution. X-ray diffraction (XRD) analysis revealed the development of an austenitic texture along the (111) and (200) planes, which was confirmed by electron backscatter diffraction (EBSD). Scanning electron microscopy (SEM) examination made it possible to identify differences in ferritic phase morphology in various deposition zones. Mechanical testing demonstrated pronounced anisotropy, with specimens deposited using a 45° overlap angle exhibiting superior mechanical properties. At the same time, uniform microhardness was observed along the deposition direction, indicating the stability of the applied strategy. In addition, residual stress measurements revealed predominantly compressive stresses away from the substrate, which may potentially enhance the resistance of components to crack initiation.

It is worth noting that an important direction in the development of DED-Arc technologies is their adaptation for the additive fabrication of small-scale metallic structures. This approach is particularly relevant for heat exchange and thermal management systems. In the study by Palumbo J. and Chandra S. [4], a cost-effective method for producing millimeter-scale metallic structures using arc spraying through a polymer mask was proposed. The method enables rapid and energy-efficient deposition of aluminum and copper structures with complex geometries and can be used for the fabrication of mini-channel heat exchangers. The authors demonstrated that photopolymer masks produced by 3D printing allow controlled formation of the geometry of the deposited structures. The deposited layers contain a dense central region, porous sidewalls, and satellite particles between neighboring elements. It was also shown that material parameters, such as density, melting temperature, and surface tension, as well as the distance between the mask and the substrate, significantly affect the morphology and porosity of the deposited elements. This approach opens up prospects for the development of low-cost functional components for heat and mass transfer applications. The arc thermal spraying process through a polymer mask and the resulting metallic structures are illustrated in Figure 3 [4]. The figure shows the main elements of the spraying setup, representative deposited structures, and SEM cross-sections of aluminum and copper deposits.

A comparative analysis of the reviewed studies [1-4] shows that the microstructure and performance of components produced by arc-based additive technologies strongly depend on heat input, deposition strategy, and process stability.

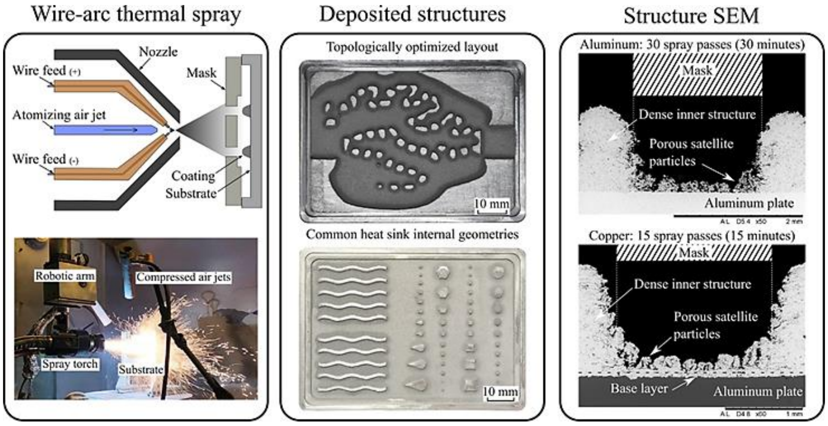

Figure 3 – Arc thermal spraying through a polymer mask: schematic of the spraying setup, representative fabricated structures, and cross-sectional SEM images of aluminum and copper deposits [4]

Low heat input modes such as CMT reduce the probability of pore and crack formation but may limit the precipitation of strengthening phases. In contrast, higher heat input processes such as pulsed GMAW promote the formation of strengthening phases but increase the risk of solidification defects. Deposition strategy and interpass temperature also influence crystallographic texture, residual stresses, and mechanical anisotropy of the deposited material. These findings indicate that careful optimization of thermal conditions and deposition parameters is essential to balance mechanical strength, structural stability, and defect control in arc-based deposition processes. Such optimization is particularly important for the fabrication of large components with complex geometries or specific functional requirements.

Overall, the reviewed studies [1-4] demonstrate the high flexibility of DED-Arc technology. It enables the fabrication of both large-scale components with controlled texture and residual stresses and miniature metallic structures produced by directed deposition through templates. However, several limitations remain, including residual stress accumulation, anisotropy of mechanical properties, and limited control of defect formation during arc-based deposition.

Surface Preparation. Along with the improvement of coating deposition methods, substrate surface preparation plays an important role in significantly enhancing coating adhesion. In the study by Gustke K. et al. [5], emphasis was placed on improving the adhesion of arc-sprayed coatings through preliminary laser surface structuring of carbon fiber–reinforced polymer (CFRP) substrates. The investigation covered nine different surface pretreatment methods, including grid-like laser structures, selective matrix removal, and laser roughening. The best results were achieved by forming grid structures with groove orientations of ±45° relative to the fiber direction, which resulted in an increase in adhesion strength of up to 186% in shear and up to 199% in tensile pull-off tests compared with grit blasting (Figure 4). It was shown that the groove depth and spacing directly affect the failure mode and the bond strength between the coating and the substrate. The importance of undercuts formed during laser processing for achieving effective mechanical interlocking was also emphasized.

Further interest in substrate surface preparation is provided by the study reported by dos Santos L. P. et al. [6], which describes a method for depositing 309L stainless steel onto polymer substrates (PP, Nylon 66, and PVC) using electric arc thermal spraying. To enhance adhesion, a bonding layer based on epoxy resin with the addition of microsilica and metallic particles was developed, resulting in favorable surface topography and improved wettability of the substrate by molten metal particles. The best results were obtained for PVC substrates, which exhibit a smaller mismatch in coefficients of thermal expansion relative to the bonding layer. The resulting coatings demonstrated not only good adhesion but also high electrical conductivity, making this approach promising for the functional metallization of plastics in various engineering applications.

In the study by Kromer R. et al. [7], an investigation was carried out aimed at improving the adhesion strength of coatings deposited by cold spraying, electric arc spraying, and atmospheric plasma spraying through preliminary substrate surface treatment using a pulsed nanosecond laser.

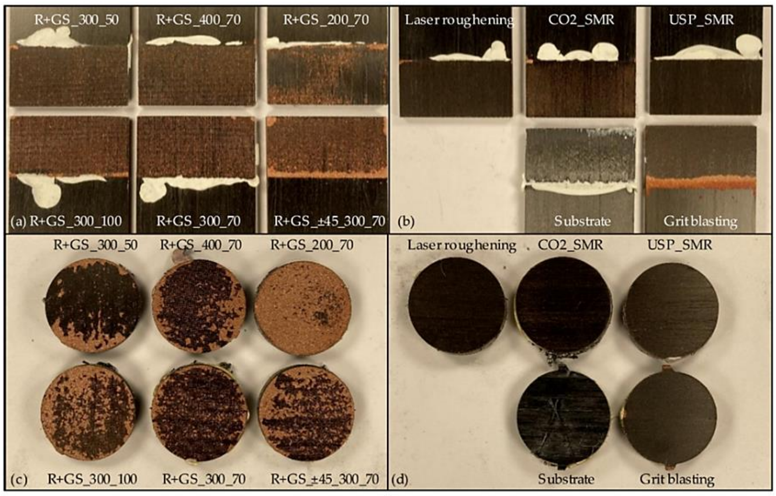

Figure 4 – Fracture surfaces of CFRP substrates with copper coatings deposited by arc spraying, illustrating different failure modes after shear tensile tests (a, b) and pull-off tests (c, d) [5]

The application of laser surface texturing makes it possible to form anchoring zones on the substrate surface, thereby promoting mechanical interlocking of the coating and improving the quality of the interfacial contact. Among the key advantages of this method are the absence of abrasive particle inclusions, minimal thermal impact on the substrate, and high processing repeatability. Fractographic analysis showed that the morphology of the laser-generated surface pattern has a significant influence on crack propagation and failure behavior; a mixed-mode fracture mechanism was identified, explaining the observed increase in adhesion strength. It is particularly important to note that laser surface treatment of lightweight alloys, such as aluminum and magnesium alloys, demonstrates high efficiency for subsequent coating deposition without the use of a bonding layer. Thus, laser surface texturing represents a promising surface preparation technology for electric arc spraying, contributing to a significant enhancement of coating-substrate adhesion strength.

A comparison of the reviewed surface preparation methods [5-7] indicates that mechanical interlocking remains the dominant mechanism governing coating adhesion in electric arc spraying. Laser surface structuring demonstrates particularly high efficiency due to the formation of controlled anchoring geometries and undercut features, which significantly increase bonding strength compared with conventional grit blasting. At the same time, the use of intermediate bonding layers, as demonstrated for polymer substrates, provides an alternative strategy for improving adhesion when direct metallurgical bonding is not possible. These approaches highlight the importance of tailoring the substrate surface morphology to achieve reliable coating-substrate interfaces.

As a result, optimization of substrate surface preparation contributes significantly to an increase in the adhesion strength of coatings produced by electric arc spraying. However, an equally important factor determining the functional characteristics of the resulting coatings is their chemical and phase composition. Depending on service conditions and the properties of the substrate material, various types of feedstock wires are used in electric arc spraying, ranging from pure metals to complex alloys and composite materials.

Zn-Al-Mg Coatings. One of the most common types of coatings produced by electric arc spraying is zinc coatings, which are widely used for sacrificial corrosion protection of aluminum and steel alloys. In the study by Yuan Z. et al. [8], it was demonstrated that the deposited zinc layer acts as a sacrificial anode, providing corrosion protection for an Al-Mn alloy. Analyses performed using GDOES, SEM, TEM, and potentiodynamic polarization confirmed that the presence of a Zn coating reduces the corrosion potential of the surface, limits the development of pitting corrosion, and promotes the formation of a corrosion potential gradient across the material thickness due to zinc diffusion into the substrate (Figure 5). This results in more stable corrosion behavior of the aluminum alloy in aggressive environments. SWAAT testing conducted over a period of 20 days revealed the absence of deep corrosion damage, indicating the effectiveness of the coating. Accordingly, the use of zinc wire in electric arc spraying represents a promising approach for the development of anticorrosion coatings for lightweight alloys.

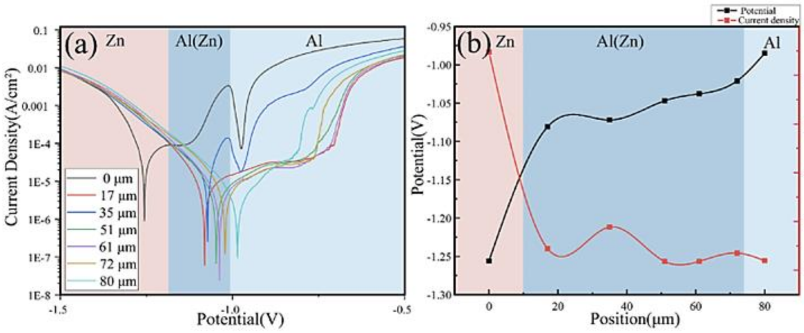

Figure 5 – Results of electrochemical corrosion testing: (a) dynamic polarization curves of the aluminum alloy sheet at different depths; (b) variation trends of corrosion potential and corrosion current density [8]

In the study by Wang S. et al. [9], the corrosion behavior of coatings deposited by electric arc spraying from aluminum-based wires alloyed with magnesium and zinc was investigated. Three compositions were examined: Al – 5%Mg (AM), AMZ50 (a mixture of Al – 5%Mg and Al – 50%Zn wires), and AMZ100 (a mixture of Al – 5%Mg and 99.9% Zn). Corrosion tests conducted in a 3.5 wt.% NaCl solution using polarization curves and electrochemical impedance spectroscopy (EIS) revealed differences in corrosion behavior between alloy and pseudo-alloy coatings (Figure 6). The AM coating exhibited the highest corrosion resistance due to the formation of a stable protective Al_2O_3 film. The addition of zinc in the AMZ50 and AMZ100 pseudo-alloys led to the formation of phase and colony segregations with different electronegativities, which promoted the formation of multiple micro-galvanic cells (MGCs) and localized dissolution. In the AMZ50 coating, corrosion predominantly developed within AZ colonies, where simultaneous dissolution of the Zn-rich (η) phase and the Al-rich (α) phase occurred, accompanied by the formation of layered double hydroxides (LDHs) exhibiting a sealing effect.

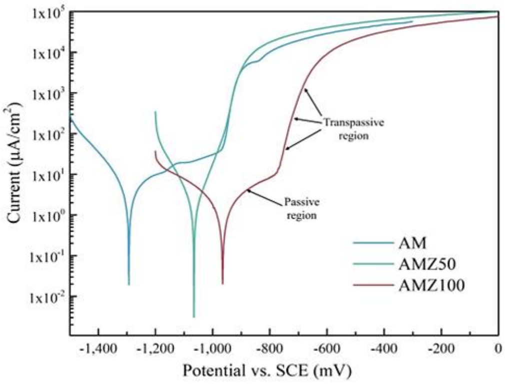

Figure 6 – Potentiodynamic polarization curves of three pseudo-alloy coatings in a 3.5 wt.% NaCl solution at room temperature

In the AMZ100 coating, Zn splats acted as anodes, while Al splats functioned as cathodes. The main corrosion products – simonkolleite and zinc carbonates – provided partial protection; however, the large anodic zinc coverage hindered repassivation, resulting in slow and continuous dissolution. Nevertheless, the presence of AM splats in the pseudo-alloy coatings effectively blocked ionic and electronic conductivity, thereby reducing the corrosion rate. In addition, these coatings provided more pronounced sacrificial protection, particularly under coating damage conditions, making them promising for practical applications.

To date, a substantial number of studies [10-20] have been reported in the scientific literature focusing on zinc-, aluminum-, and magnesium-based wires used in electric arc spraying processes. These studies address both the characteristics of the feedstock wires and the morphology, phase composition, adhesion, and corrosion resistance of the resulting coatings. Particular attention is given to the development of new pseudo-alloy compositions and their influence on the mechanisms of protective layer formation, sacrificial protection, and resistance to aggressive environments. Specifically, zinc-based (Zn), zinc–aluminum (Zn–Al), aluminum–magnesium (Al–Mg), and complex

Zn–Al–Mg alloy wires exhibit different types of galvanic activity, leading to the formation of multiple galvanic cells, which significantly affects their anticorrosion performance. The summarized results of these studies provide a basis for the further selection of optimal wire compositions in accordance with specific service requirements.

Overall, the reviewed studies show that the corrosion behavior of arc-sprayed coatings is governed by electrochemical interactions between coating phases. Al–Mg coatings generally exhibit high corrosion resistance due to the formation of stable oxide films. In contrast, Zn-containing coatings provide protection mainly through sacrificial corrosion mechanisms. Pseudo-alloy systems containing both Al and Zn may form micro-galvanic couples. These couples can accelerate localized corrosion under certain conditions. Therefore, the corrosion performance depends not only on the alloy composition but also on phase distribution and electrochemical interactions. The representative properties of coatings produced by electric arc spraying reported in the literature are summarized in Table 1.

Table 1 – Properties of coatings produced by electric arc spraying

№	Material	Main functional property	Key results
1	Zn wire	Sacrificial corrosion protection	Zn coating acts as sacrificial anode protecting Al alloy [8]
2	Al-5Mg wire	Corrosion resistance	Stable Al_2O_3 film formation improves corrosion resistance [9]
3	Al-5Mg + Zn wires	Sacrificial protection	Formation of micro-galvanic cells affecting corrosion behaviour [9]
4	Metcoloy II alloy wire	Oxidation resistance	Protective Cr and Al oxide layers at high temperature [21]
5	NiCrMoAl alloy wire	Corrosion resistance	Oxide shell formation around splats after heat treatment [25]
6	(AlCoCrFeNiSi)+WC cored wire	Hardness and adhesion	Increase in microhardness (up to ~529 HV0.1) and adhesion strength (up to ~40 MPa) due to WC addition [27]
7	FeCrMoNbB + FeCMnSi wires	Corrosion resistance	Improved corrosion resistance due to passive compounds [37]

As shown in Table 1, the functional performance of arc-sprayed coatings strongly depends on the chemical composition of the material and the resulting phase structure of the coating.

Alloy and Composite Coatings. Continuing the review of various types of wires and coatings produced by electric arc spraying, particular interest is associated with a study focused on the application of Metcoloy II coatings. In the work by Pérez-Muñoz D. et al. [21], a Metcoloy II coating deposited by electric arc thermal spraying onto ASTM A53 Grade B steel demonstrated high effectiveness under cyclic oxidation conditions at elevated temperatures (500°C and 700°C). The test results showed that the Metcoloy II coating significantly improves oxidation resistance compared with the uncoated material due to the formation of protective chromium and aluminum oxide layers. These oxides contribute to the retardation of oxidation processes and limit mass gain, thereby preserving surface integrity. Good adhesion of the coating to the substrate ensured stable protection throughout the entire testing cycle (Figure 7). At the same time, it was observed that at a temperature of 700°C the coating undergoes structural changes, including increased porosity, reduced thickness, and the formation of microcracks, which leads to a degradation of protective performance and more intensive oxidation of the substrate. Nevertheless, even at high temperatures, Metcoloy II retains partial effectiveness, while at 500 °C it exhibits particularly stable performance. This makes it a promising candidate for applications under high-temperature service conditions, such as thermal power generation and boiler equipment. Further studies are recommended to improve the coating structure and enhance its thermal stability under more severe operating regimes.

Another important direction in electric arc spraying involves copper-based coatings, as well as coatings alloyed with iron, chromium, stainless steel, and composite systems, including those containing nickel, cobalt, molybdenum, and carbon steels. Such coatings are widely applied in various fields, including the metallization of non-conductive materials, where a combination of high mechanical strength, corrosion resistance, and specific functional properties is required. The use of diverse feedstock wires and alloy compositions enables the development of coatings with optimized characteristics for anticorrosion protection, enhanced wear resistance, and antifouling performance.

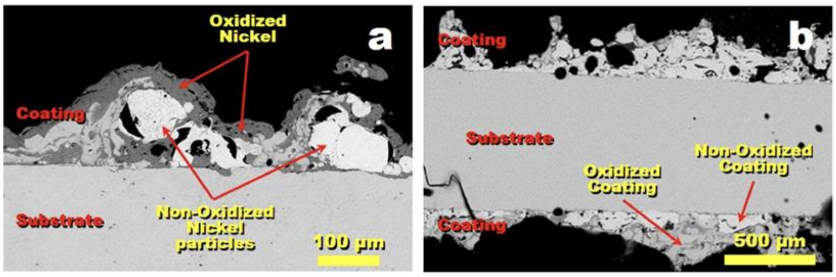

Figure 7 – (a) Cross section of the coated specimen after 100 oxidation cycles at 700°C;
(b) cross section of the coated specimen after 500 oxidation cycles at 700°C [21]

In the study by Nigam S., Mahapatra S. S., and Patel S. K. [22], devoted to the deposition of a copper layer onto ABS using electric arc spraying, characteristic lamellar coating structures with high density and strength were identified. Microhardness and surface roughness were thoroughly analyzed, providing insight into the quality and nature of the formed coating. Optimization of process parameters using the Taguchi method and analysis of variance (ANOVA) made it possible to identify the most significant factors affecting coating density and to determine optimal conditions for producing a highly dense and mechanically robust layer. Consequently, copper coatings deposited onto ABS by electric arc spraying demonstrate promising performance, combining good adhesion and mechanical durability, which expands the potential applications of this metallization technique for non-conductive materials.

In the study by Fang L. et al. [23], innovative aluminum-copper coatings fabricated by arc spraying using in-house developed Al-Cu cored wires were presented, providing combined anticorrosion and antifouling protection. Microstructural analysis revealed a uniform distribution of copper particles within the coating and partial interaction between copper and the aluminum matrix, leading to the formation of the Al_2Cu intermetallic compound. This interaction contributes to the retention of copper within the coating and prevents its rapid leaching in aqueous environments. Electrochemical tests conducted in artificial seawater demonstrated that the presence of copper does not deteriorate the corrosion resistance of aluminum coatings. The antifouling performance of the coatings was confirmed by settlement and colonization tests involving E. coli, Bacillus sp., and typical marine algae. These properties are attributed to the continuous release of copper ions exhibiting antimicrobial activity. The results of the study indicate the promising potential of arc spraying with cored wires for the development of multifunctional protective coatings intended for marine applications.

In the study by Dubovoy O.M. et al. [24], coatings were produced using titanium carbide in a free (unbound) form as a strengthening phase. It was established that spraying process parameters have a direct influence on the content of the strengthening phase in the coating and, consequently, on its physical and mechanical properties. Optimal processing regimes ensure high adhesion strength between the coating and the substrate and enhance performance characteristics, which is particularly important for applications in the mining industry and other industrial sectors associated with severe equipment wear.

Using the example of the study by Srichen A., Linjee S., and Banjongprasert C. [25], the influence of heat treatment on the microstructure and corrosion properties of NiCrMoAl alloy coatings was investigated. Coatings produced by electric arc spraying were subjected to heat treatment at temperatures of 500-700°C for durations of 10 and 30 days. It was established that prolonged exposure to elevated temperatures promotes the formation of a large amount of oxides and internal stresses, which leads to crack formation at the boundaries of molten particles and a deterioration in corrosion resistance. In contrast, heat treatment at 500°C contributed to maintaining a high concentration of alloying elements (Cr, Mo, and Si) within the splats and to the formation of a dense oxide shell around the particles, thereby providing enhanced corrosion protection (Figure 8). Thus, the appropriate selection of heat treatment parameters plays a key role in ensuring the anticorrosion performance of NiCrMoAl-based coatings.

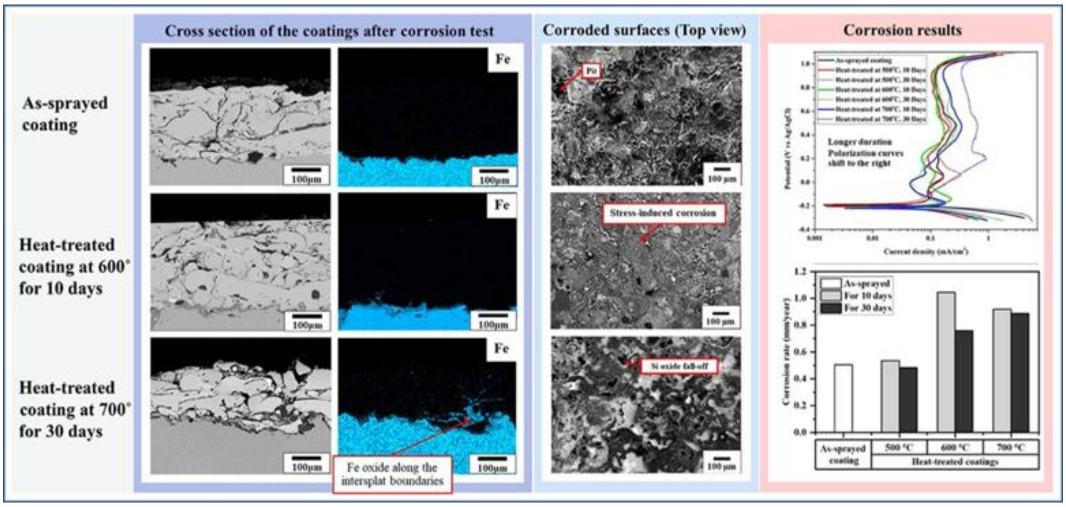

Figure 8 – Microstructure, surface morphology, and corrosion properties of NiCrMoAl coatings produced by electric arc spraying before and after heat treatment [25]

In another study by Pan P. et al. [26], the behavior of an amorphous Fe–Cr–Mo–based coating produced by electric arc spraying was investigated under conditions simulating a biomass combustion environment at temperatures of 500°C and 600°C. Such coatings are considered potentially cost-effective solutions to the problem of chlorine-induced hot corrosion in biomass-fired boilers. The study showed that Fe and Cr elements within the coating underwent chlorination followed by evaporation, which led to the formation of Cr-depleted zones and a deterioration of protective properties. At the same time, Mo-containing regions exhibited high resistance to the action of aggressive gaseous species; however, with increasing temperature, they became more susceptible to electrochemical attack. In addition, the presence of cracks and micropores in the coating structure facilitated the penetration of aggressive species into the material, thereby reducing the overall corrosion resistance. The obtained results highlight the importance of optimizing coating microstructure and density to enhance the protection efficiency of metallic components under high-temperature service conditions.

Another promising direction involves coatings based on high-entropy alloys (HEAs) reinforced with carbides. In the study by Bello Z. A. et al. [27], coatings with the composition $(AlCoCrFeNiSi)_{100-x}(WC)_x$(x = 0,20 and 40 wt.%) were produced by high-velocity arc spraying onto a Q235 steel substrate. The introduction of WC particles had a significant effect on the phase composition and properties of the coatings. In the absence of WC, the body-centered cubic (BCC) phase was dominant; however, with the addition of 20 and 40 wt.% WC, the microstructure contained a combination of BCC and face-centered cubic (FCC) phases, as well as carbide phases such as W_3C and Cr_7C_3. The presence of WC contributed to a reduction in the average crystallite size from 14.75 nm to 10.34 nm, an increase in microhardness (up to 529.9 HV0.1), and an improvement in adhesion strength to the substrate (up to 40.23 MPa). Mechanical testing demonstrated that the dominant failure mechanism depends on the content of the reinforcing phase: in the absence of WC, interfacial failure (adhesion failure) prevailed, whereas at high carbide contents, cohesive (glue-type) failure was dominant, indicating improved coating cohesion. According to SEM and XPS analyses, the enhanced corrosion resistance is associated with the formation of passive oxide layers that slow down anodic dissolution processes.

Based on the analysis of the reviewed studies, the main process parameters influencing the microstructure and performance of arc-sprayed coatings can be systematized. A summary of the key processing parameters and their influence on coating structure and properties reported in the literature is presented in Table 2.

As shown in Table 2, heat input, deposition strategy, and feedstock composition are among the most influential parameters controlling the microstructure and functional performance of arc-sprayed coatings.

Table 2 – Influence of processing parameters on structure and properties of arc-sprayed coatings

№	Process parameter	Effect on microstructure	Effect on properties
1	Heat input	Phase precipitation and grain growth	Strength variation and crack formation [1]
2	Deposition strategy	Crystallographic texture development	Mechanical anisotropy of deposited structures [3]
3	Interpass temperature	Residual stress distribution and microstructure evolution	Crack resistance and mechanical stability [1,3]
4	Surface preparation	Formation of anchoring structures and roughness	Adhesion strength improvement [5,7]
5	Feedstock composition	Phase distribution and oxide formation	Corrosion and wear resistance [8,9]
6	Carbide reinforcement (WC)	Grain refinement and carbide phase formation	Increased hardness and adhesion strength [27]

Multicomponent Coatings. Analysis of the literature data and experimental results indicates that coatings produced by electric arc spraying exhibit a wide range of performance characteristics, which depend primarily on the chemical composition of the feedstock materials [28-36]. Copper-based coatings are widely applied due to their high thermal conductivity, electrical conductivity, and antimicrobial properties. To enhance their thermal and corrosion resistance, modifying additions such as iron, chromium, and nickel are commonly used. Coatings alloyed with iron and chromium demonstrate high corrosion resistance in aggressive environments, including acidic media and chloride-rich conditions. The incorporation of stainless steel into coating compositions provides resistance to oxidation and wear under elevated temperatures and mechanical loads. Composite coatings reinforced with particles such as carbides, nitrides, and other refractory compounds are characterized by increased hardness, adhesion strength, and wear resistance. Nickel and cobalt contribute to improved mechanical and anticorrosion properties, particularly under high-temperature service conditions and in aggressive environments. Molybdenum enhances resistance to chloride- and sulfate-induced corrosion and improves the structure of protective oxide layers. Carbon steels, used either as substrates or as components of coating systems, provide a favorable combination of mechanical strength and cost effectiveness. Thus, rational selection of coating composition and spraying regimes makes it possible to produce coatings with tailored functional properties for applications across various industrial sectors, ranging from mechanical engineering to power generation and the chemical industry.

Considering the diversity of components used for coating formation, it becomes evident that a key role is played not only by the selection of individual materials but also by the possibility of their combination. The development of multicomponent systems and the adaptation of feedstock material compositions make it possible to significantly expand the functional characteristics of coatings. In this context, one of the currently relevant directions in electric arc spraying is the production of coatings based on mixtures of different wires that differ in chemical composition and structure.

A promising example of this approach is presented in the study by Rojas-Molano et al. [37], in which a coating formed from FeCrMoNbB (140MXC) and FeCMnSi (530AS) wires using twin-wire arc spraying (TWAS) technology was investigated. The study demonstrated that the combination of these two wires makes it possible to produce a coating with enhanced corrosion resistance due to the formation of stable passive compounds on the surface, such as Cr_2O_3, FeB, Nb_2O_5, and MoO_3 (Figure 9). The authors applied the Taguchi method (L9 orthogonal array) to optimize the spraying process parameters. It was found that the corrosion resistance of the coating is directly influenced by structural defects, including pores, microcracks, and unmelted particles formed during spraying; however, these effects can be effectively mitigated under optimized processing conditions and in the presence of appropriate alloying elements. The potential occurrence of galvanic corrosion resulting from contact between components with different electrochemical potentials was also highlighted; nevertheless, with a proper combination of material composition and spraying regimes, this effect can be significantly reduced. This study demonstrates the potential of coatings based on mixed 140MXC and 530AS wires as an effective approach to improving corrosion resistance, particularly under aggressive environmental conditions. It further emphasizes the importance of material combination and comprehensive multilevel analysis in the development of next-generation high-protection coatings.

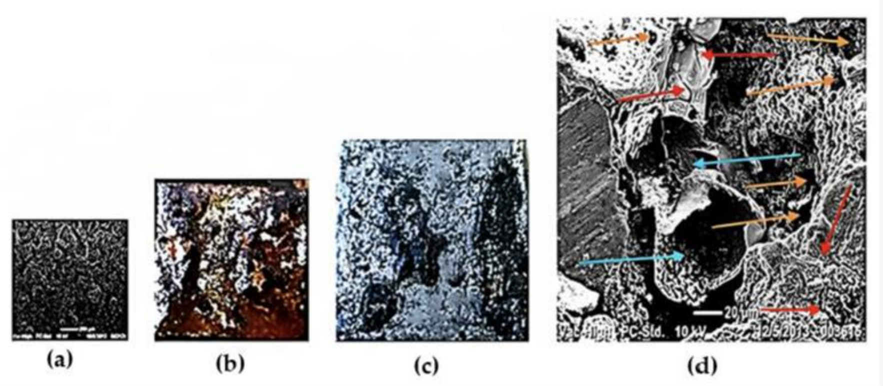

Figure 9 – Morphology of 140MXC-530AS mixed coatings after exposure to salt spray testing: (a) SEM image of the initial surface condition before testing; (b) rust formation after salt spray exposure; (c) rust removal by ultrasonic cleaning; (d) SEM image of the final surface condition after testing [37]

The reviewed studies on advanced coating systems demonstrate that the introduction of multicomponent alloys and ceramic reinforcing phases significantly expands the functional capabilities of electric arc sprayed coatings. In particular, carbide-reinforced and high-entropy alloy coatings provide improved hardness, wear resistance, and corrosion stability due to the formation of complex phase structures and refined microstructures. However, challenges related to coating porosity, oxidation during spraying, and structural heterogeneity remain important factors limiting coating performance. Further optimization of spraying parameters and feedstock design is therefore required to fully exploit the potential of these advanced coating systems.

Industrial applicability and process characteristics of electric arc spraying. Electric arc spraying is widely recognized as a productive and industrially scalable thermal spray technology. It uses wire feedstock and relatively simple equipment, which contributes to high process productivity. In general, electric arc spraying is characterized by relatively high deposition rates and is therefore suitable for large-scale protective coating applications. Several studies have investigated the influence of process parameters on coating formation. Newbery and Grant [31] demonstrated that arc voltage fluctuations strongly influence droplet formation and particle fragmentation during wire arc spraying. Variations in arc stability affect particle size distribution and coating porosity. Gedzevicius and Valiulis [32] analyzed the influence of spraying parameters such as arc current, atomizing gas pressure, and stand-off distance on coating structure and properties. Their results showed that atomizing gas pressure affects particle atomization and coating uniformity.

Rodriguez et al. [33] compared aluminum coatings produced by flame spraying and electric arc spraying and demonstrated differences in coating formation. Hussary and Heberlein [34] investigated the mechanisms of metal breakup and particle formation during arc spraying and showed that atomization conditions strongly influence droplet fragmentation. Wilden et al. [35] reported that wire composition and arc parameters affect coating microstructure and adhesion. Wagner [36] demonstrated that wire feed rate and atomizing gas pressure influence coating density and mechanical properties.

Overall, these studies show that the performance of arc-sprayed coatings strongly depends on process parameters controlling particle formation and coating microstructure. Arc stability, atomizing gas pressure, and wire feed rate can be considered the key technological parameters of the process. Their optimization is essential for balancing coating productivity and microstructural quality in practical applications.

Research gaps and future directions. Despite significant progress in the development of electric arc sprayed coatings, several challenges remain. Many studies focus on individual process parameters, whereas the combined influence of arc stability, atomizing gas pressure, and wire composition is still insufficiently understood. In addition, the relationship between particle formation mechanisms and the resulting coating microstructure requires further investigation. Future research should focus on integrated optimization of technological parameters, feedstock materials, and coating structure. Particular attention should be given to improving coating density, reducing oxidation during spraying, and enhancing corrosion and wear resistance. Such studies will contribute to improving the reliability and industrial applicability of arc-sprayed coatings.

Conclusion

This review demonstrates that electric arc spraying remains a relevant and rapidly evolving technology for the production of functional coatings. In contrast to many existing studies that focus on individual coating systems or specific process parameters, this review provides a comparative analysis of feedstock materials, surface preparation strategies, and processing conditions, highlighting the relationships between process parameters, coating microstructure, and functional properties.Recent research shows a clear trend toward improving coating performance through the integration of advanced deposition strategies, optimized process parameters, and novel feedstock materials. Research in the field of DED-Arc, the use of mixed feedstock wires, laser substrate preparation, and additive manufacturing approaches open new opportunities for improving coating properties, including mechanical strength, corrosion resistance, and thermal stability. The reviewed studies indicate that coating performance in electric arc spraying follows a clear process–structure–property relationship. Spraying parameters influence particle formation, which in turn determines coating microstructure and functional properties. Particular importance should be given to the integrated optimization of feedstock materials, spraying regimes, and substrate surface preparation. Such approaches enable the development of coatings that meet the requirements of modern industries, including mechanical engineering, power generation, marine engineering, and aerospace applications. Future research should focus on the development of multicomponent coating systems, further investigation of high-entropy and cermet coatings, and improvement of coating–substrate interfaces in order to enhance coating reliability and durability in demanding service environments.

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Ж.Б. Сағдолдина[1,2], А.Б. Леонидова[2*], А.Ж. Жасұлан[2,3], А.Б. Шынарбек[3], Ж. Турар[4]
[1]Сәрсен Аманжолов атындағы Шығыс Қазақстан мемлекеттік университеті,
070000, Қазақстан Республикасы, Өскемен қаласы, 30-шы Гвардиялық дивизия көш., 34
[2]Шәкәрім университеті,
071412, Қазақстан Республикасы, Семей қ., Физкультурная көш., 4
[3]Инженерлік орталық, Шәкәрім университеті,
071412, Қазақстан Республикасы, Семей қ., Глинка көш., 20 А
[4]Сакарья Университеті,
54050, Түркия, Сакарья қ., Академиолу көш., 5-20
*e-mail: aiymleonidova1994@gmail.com

ЭЛЕКТРДОҒАЛЫҚ БҮРКУ ӘДІСІМЕН ҚАЛЫПТАСТЫРЫЛАТЫН ЖАБЫНДАРДЫ МОДИФИКАЦИЯЛАУДЫҢ ЗАМАНАУИ ТӘСІЛДЕРІ (ШОЛУ МАҚАЛАСЫ)

Бұл шолу мақаласында электр доғалы бүрку әдісімен алынатын жабындардың пайдалану сипаттамаларын арттырудың заманауи тәсілдері қарастырылады. Ерекше назар электр доғасы арқылы энергияны бағыттап тұндыру технологиясы (Directed Energy Deposition, DED-Arc) саласындағы зерттеулерге аударылған, оның ішінде бүрку параметрлерін таңдау, негіз бетінің дайындалуы, сондай-ақ жаңа типтегі сымдар мен композициялық материалдарды қолдану мәселелері қамтылады. Коррозияға төзімді, термиялық төзімді және тозуға төзімді қорғанысқа арналған бастапқы материалдарды дамытудағы жетістіктер қарастырылған. Атап айтқанда, Zn, Al-Mg және Zn-Al-Mg жүйелері, биологиялық обрастануға қарсы қолдануға арналған Al-Cu ұнтақты-сымды материалдар, тот баспайтын болаттар мен NiCrMoAl қорытпалары, керметтік жабындар, сондай-ақ вольфрам карбидімен (WC) упрочнённен жоғары энтропиялы қорытпалар талданады. Жабындардың адгезиялық беріктігін арттыру үшін лазерлік беттік текстуралау әдістерін қолдану және электр доғалы бүрку технологиясын электрөткізбейтін негіздерге бейімдеу бойынша соңғы нәтижелер келтірілген. Сонымен қатар «процесс-құрылым-қасиет» өзара байланысының жабындардың пайдалану қасиеттеріне әсері қысқаша талданады. Жалпыланған деректер электр доғалы бүрку технологиясының әртүрлі өнеркәсіптік қолдану салаларында алдын ала берілген қасиеттері бар функционалдық жабындарды алу үшін икемді әрі экономикалық тұрғыдан тиімді әдіс екенін көрсетеді.

Түйін сөздер: *электрдоғалық бүрку; DED-Arc; жабындар; адгезия; коррозияға қарсы қорғаныс.*

Ж.Б. Сагдолдина[1,2], А.Б. Леонидова[2*], А.Ж. Жасұлан[2,3], А.Б. Шынарбек[3], Ж. Турар[4]
[1]Восточно-Казахстанский университет имени Сарсена Аманжолова,
070000, Республика Казахстан, г. Усть-Каменогорск, ул. 30-й Гвардейской дивизии, 34,
[2]Шәкәрім университет, 071412, Республика Казахстан, г. Семей, ул. Физкультурная, 4
[3]Инжиниринговый центр, Шәкәрім университет,
071412, Республика Казахстан, г. Семей, ул. Глинки, 20 А
[4]Университет Сакарья, 54050, Турция, г. Сакарья, ул. Академийолу, 5-20
*e-mail: aiymleonidova1994@gmail.com

СОВРЕМЕННЫЕ ПОДХОДЫ К МОДИФИКАЦИИ ПОКРЫТИЙ, ФОРМИРУЕМЫХ МЕТОДОМ ЭЛЕКТРОДУГОВОГО НАПЫЛЕНИЯ (ОБЗОР)

В данной обзорной статье рассмотрены современные подходы к повышению эксплуатационных характеристик покрытий, получаемых методом электродугового напыления. Особое внимание уделено исследованиям в области направленного осаждения энергии электрической дугой (Directed Energy Deposition, DED-Arc), включая выбор параметров напыления, подготовку поверхности подложки, а также применение новых типов проволок и композиционных материалов. Проанализированы достижения в разработке исходных материалов для коррозионностойкой, термостойкой и износостойкой защиты, охватывающие системы Zn, Al–Mg и Zn–Al–Mg, порошково-проволочные материалы Al–Cu для противообрастающих применений, нержавеющие стали и сплавы NiCrMoAl, керметные покрытия, а также высокоэнтропийные сплавы, упрочнённые карбидом вольфрама (WC). В статье представлены современные результаты по повышению адгезии покрытий за счёт лазерной текстуризации поверхности, а также по адаптации технологии электродугового напыления для нанесения покрытий на непроводящие подложки. Кроме того, кратко рассмотрено влияние взаимосвязи «процесс–структура–свойства» на эксплуатационные характеристики покрытий. Обобщённые результаты подчёркивают потенциал электродугового напыления как гибкой и экономически эффективной технологии для формирования функциональных покрытий с заданными свойствами, предназначенных для широкого спектра промышленных применений.

Ключевые слова: *электродуговое напыление, DED-Arc, покрытия, адгезия, антикоррозионная защита.*

Сведения об авторах

Жұлдыз Болатқызы Сағдолдина – PhD, ассоциированный профессор, Восточно-Казахстанский университет имени Сарсена Аманжолова, г. Усть-Каменогорск, Республика Казахстан; e-mail: sagdoldina@mail.ru. ORCID: https://orcid.org/0000-0001-6421-2000.

Айым Бауыржанқызы Леонидова* – докторант специальности «Техническая физика», Шәкәрім университет, Исследовательская школа физических и химических наук, кафедра Техническая физика и теплоэнергетика, г. Семей, Республика Казахстан; e-mail: aiymleonidova1994@gmail.com. ORCID: https://orcid.org/0009-0008-2981-2041.

Айнұр Жасұланқызы Жасұлан – докторант специальности «Техническая физика», Шәкәрім университет, Исследовательская школа физических и химических наук, кафедра Техническая физика и теплоэнергетика, г. Семей, Республика Казахстан, старший научный сотрудник Инжинирингового центра; e-mail: ainur.99.99.99@mail.ru. ORCID: https://orcid.org/0009-0001-5887-0135.

Айбек Бақытжанұлы Шынарбек – докторант специальности «Технологические машины и оборудование», Шәкәрім университет, старший научный сотрудник Инжинирингового центра; г. Семей, Республика Казахстан; e-mail: Shinarbekov16@gmail.com. ORCID: https://orcid.org/0009-0009-2877-5178.

Жанабай Турар – магистрант, Университет Сакарья, г. Сакарья, Турция; e-mail: turarjanabay@gmail.com. ORCID: https://orcid.org/0009-0004-6202-112X.

Авторлар туралы мәліметтер

Жұлдыз Болатқызы Сағдолдина – PhD, Ассоциированный профессор, Сәрсен Аманжолов атындағы Шығыс Қазақстан мемлекеттік университеті, Өскемен қаласы Қазақстан Республикасы; e-mail: sagdoldina@mail.ru. ORCID: https://orcid.org/0000-0001-6421-2000.

Айым Бауыржанқызы Леонидова* – «Техникалық физика» мамандығының докторанты, Шәкәрім университеті, Физика және химия ғылымдары зерттеу мектебі, Техникалық физика және жылуэнергетика кафедрасы, Семей қ., Қазақстан Республикасы; e-mail: aiymleonidova1994@gmail.com. ORCID: https://orcid.org/0009-0008-2981-2041.

Айнұр Жасұланқызы Жасұлан – «Техникалық физика» мамандығының докторанты, Шәкәрім университеті, Физика және химия ғылымдары зерттеу мектебі, Техникалық физика және жылуэнергетика кафедрасы, Қазақстан Республикасы, Инженерлік орталықтың аға ғылыми қызметкері; e-mail: ainur.99.99.99@mail.ru. ORCID: https://orcid.org/0009-0001-5887-0135.

Айбек Бақытжанұлы Шынарбек – «Технологические машины и оборудование» мамандығының докторанты Инженерлік орталықтың аға ғылыми қызметкері, Шәкәрім университеті, Семей қ., Қазақстан Республикасы; e-mail: Shinarbekov16@gmail.com. ORCID: https://orcid.org/0009-0009-2877-5178.

Жанабай Турар – Сакарья университетінің магистранты, Сакарья қ., Түркия; e-mail: turarjanabay@gmail.com. ORCID: https://orcid.org/0009-0004-6202-112X.

Information about the authors

Zhuldyz Sagdoldina – PhD, Associate Professor, Sarsen Amanzholov East Kazakhstan State University, Ust-Kamenogorsk, Republic of Kazakhstan; e-mail: sagdoldina@mail.ru. ORCID: https://orcid.org/0000-0001-6421-2000.

Aiym Leonidova* – PhD student in the specialty «Technical Physics», Shakarim University, Research School of Physical and Chemical Sciences, Department of Technical Physics and Heat Power Engineering, Semey, Republic of Kazakhstan; e-mail: aiymleonidova1994@gmail.com. ORCID: https://orcid.org/0009-0008-2981-2041.

Ainur Zhassulan – PhD student in the specialty «Technical Physics», Shakarim University, Research School of Physical and Chemical Sciences, Department of Technical Physics and Heat Power Engineering, Semey, Republic of Kazakhstan, Senior Researcher, Engineering Center; e-mail: ainur.99.99.99@mail.ru. ORCID: https://orcid.org/0009-0001-5887-0135.

Aibek Shynarbek – PhD student, Engineering Center, Shakarim University, Semey, Kazakhstan; e-mail: Shinarbekov16@gmail.com. ORCID: https://orcid.org/0009-0009-2877-5178.

Zhangabay Turar – Master's student in Physics, Sakarya University, Sakarya, Turkey; e-mail: turarjanabay@gmail.com. ORCID: https://orcid.org/0009-0004-6202-112X.

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А.Ж. Сағындықова[1], Н.А. Заец[2], Р.А. Жамашева[3], Н.Н. Нұрғалиев[4*]

[1]Гумарбек Дәукеев атындағы Алматы энергетика және байланыс университеті,
050013, Қазақстан Республикасы, Алматы, Байтұрсынов көшесі,127
[2]Берлин қолданбалы ғылымдар университеті,
10963, Германия, Берлин, Дессауэр көшесі, 3/5
[3]Алматы технологиялық университеті,
050012, Қазақстан Республикасы, Алматы, Төле би көшесі,100
[4]Шәкәрім университеті,
071412, Қазақстан Республикасы, Семей, Глинки көшесі, 20
*e-mail: n.nurgaliyev@shakarim.kz

ИНДУКЦИЯЛЫҚ ҚЫЗДЫРУ ЖҮЙЕЛЕРІНЕ АРНАЛҒАН ЖИІЛІК ТҮРЛЕНДІРГІШІН МАТЕМАТИКАЛЫҚ МОДЕЛЬДЕУ ЖӘНЕ ЭКСПЕРИМЕНТТІК ЗЕРТТЕУЛЕР

Аңдатпа: *Мақалада ауыл шаруашылығы машина жасау, автомобиль өнеркәсібі және металл өңдеу сияқты әртүрлі салаларда индукциялық жылыту жүйелерін әзірлеу және қолдану талқыланады. Индукциялық қондырғылар мен дәстүрлі жылыту әдістерінің салыстырмалы талдауы келтірілген, олардың жоғары қыздыру жылдамдығы мен тиімділігі, процесті басқарудың жақсаруы және энергия тұтынудың төмендеуі сияқты артықшылықтары көрсетілген. Индукциялық қыздыру жүйелеріне арналған жиілік түрлендіргішінің математикалық моделі көп өлшемді айнымалылардың динамикасын сипаттайтын дискретті теңдеулер жүйесіне негізделген. Қолданыстағы тәсілдерден айырмашылығы, бұл модель жұмыс жиіліктерінің оңтайлы диапазонын ескереді, қуат транзисторларының санын азайтады және орнатылған қуатты ескереді, мұның бәрі жоғары энергия тиімділігін сақтайтынын байқатады. Зерттеу аясында бір фазалы және үш фазалы қуат көзімен 2-20 кГц диапазонында жұмыс істейтін прототиптік жиілік түрлендіргіші және 6 кВт индуктор әзірленіп, шығарылды. Эксперименттік зерттеулер ұсынылған модельдің жарамдылығын және оның нақты технологиялық жағдайларда қолданылуын растады. Жұмыстың практикалық маңыздылығы машина жасау мен ауылшаруашылық машиналарында оңтайлы индукциялық қыздыру технологияларын таңдау үшін әзірленген модель мен прототипті пайдалану мүмкіндігінде жатыр, осылайша сенімділіктің артуын, энергия тұтынудың төмендеуін және шығындардың төмендеуін қамтамасыз етеді. Нәтижелер ұсынылған модельдің жеткіліктілігін көрсетті және оның практикалық қолданылуын растады.Түрлендіргіш параметрлеріндегі өзгерістер оңтайлы индукциялық қыздыру режимін таңдауға айтарлықтай әсер ететіні көрсетілді, бұл білім беру мақсаттары үшін де, өнеркәсіптік енгізу үшін де практикалық маңызды.*

Түйін сөздер: *жиілік түрлендіргіштері, индукциялық қыздыру, транзисторлық модуль, үш фазалы түзеткіш, инвертор, IGBT индукциялық қыздыру жүйесі.*