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Effect of Voltage on Properties of 30HGSA Steel Coatings by Supersonic Arc Metallization Method

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ABSTRACT

This work is a study aimed at optimizing the process of superarc metallization, with a focus on the effect of voltage on the properties of the spraying coatings. In this work, 30HGSA grade steel wire was used for the coating of 45 steel, widely used in mechanical engineering. The use of supersonic arc metallizer SX-600 allowed to obtain coatings at different voltages (32 V, 38 V and 44 V) and the same current strength. Various metallization process parameters such as material feed rate, voltage, current, distance and nozzle geometry are discussed in this paper. Using various analytical techniques including X-ray diffraction analysis, microscopy, microhardness and corrosion resistance tests, the qualities of the coatings were evaluated. Particular attention was paid to analyzing the phase composition of the coatings, porosity, substrate bond strength and tribological characteristics. It was found that the voltage during the supersonic arc metallization process has a significant effect on these characteristics. The selected optimum voltage allows to obtain dense and homogeneous coatings with improved performance properties. The results of the study revealed that the best physical and mechanical properties were exhibited by the sample processed at 38 V, which showed lower porosity and improved strength characteristics compared to the other samples. These findings can be used to improve manufacturing processes in industries such as automotive and mechanical engineering, where restoration and improved performance of worn parts is required.

Keywords: supersonic arc metallization, wire, coating, steel, structure, elemental analysis, corrosion, martensite, steel cladding wire, steel wire coating.

INTRODUCTION

Metal losses due to wear and corrosion of machine parts and metal structures account for approximately 30% of their mass. A promising approach to reducing losses is improving the properties of the surface in contact with the external environment. Research and practical developments show that this can increase the lifespan of products several times over. [1] Gas-thermal spraying (GTS) methods for coating deposition are actively developing here. The analysis results indicate that thermal spraying significantly contributes to the economy of developed countries. GTS methods involve dispersing a sprayed material accelerated by a gas jet. The surface of the part receiving the coating remains solid. This characteristic results in minimal thermal deformation and, in many cases, no structural changes in the part. [2, 3] Additionally, there are minor restrictions on the composition of applied materials. This makes GTS attractive for improving the operational characteristics of products. Gas-flame (GF) [4–6], detonation (D) [7], plasma (P) [8, 9], CGS [10, 11], cathodic arc metallization (PVD) [12], air-plasma (AP) [13] and electric-arc metallization (EAM) [14] are among the main methods.

The ratio of these parameters determines the potential application areas of specific GTS methods to improve surface properties. Among the methods of applying gas-thermal coatings, the arc metallization (EAM) process appears preferable in terms of thermal efficiency, cost of sprayed materials, and ease of maintenance. According to the techno-economic assessment [10–15], in terms of relative cost, EAM coatings are 3–10 times cheaper than those obtained by other GTS methods while ensuring high strength. During EAM, heating and melting of the sprayed material occur due to the heat of the electric arc burning between the electrodes, from which the sprayed material is formed. This reduces the amount of heat loss during heating and melting of the metal compared to other GTS processes, where heat generation and its consumption for melting the sprayed material are separated in time and space. EAM is a process in which metal wire or powder is melted using an electric arc and then applied to the substrate surface. The main stages include surface preparation and application of the metallic coating. During the process, the material is melted in an arc torch and then sprayed onto the substrate surface using compressed air. The droplets of melted material solidify, forming the coating. The properties of these coatings depend on various parameters such as material feed rate, voltage, current, distance, and nozzle geometry [16, 17].

New coating processes and materials with suitable properties improve the functionality and applications of arc-sprayed coatings in various environments. In addition to focusing on arc-spraying parameters, the development of high-performance and multifunctional coatings provides arc-spraying flexibility to produce coatings with improved properties [18, 19]. Crystalline and amorphous iron-based coatings have great potential for anti-corrosion and anti-wear applications. They are also suitable candidates for medium and high temperature applications because of their good oxidation properties [20]. Spraying parameters, such as compressed air pressure and particle size, voltage, wire feed speed, affect the structure of the coating.

The purpose of this work is to study the influence of voltage on the properties of a coating made of 30KhGSA wire on the surface of 45 steel using the method of supersonic supersonic arc metallization.

MATERIALS AND METHODS

Materials and equipment for the experiment

A 30HGSA grade steel wire with a diameter of 1.6 mm was used in the coating process. Chemical composition of 30 HGSA steel is shown in Table 1. Substrate samples were made in the form of disk segments constituting a quarter of a disk with a diameter of 65 mm and a thickness of 10 mm. These samples were made from steel rod grade 45 (according to GOST 1050–2013). This choice is due to the widespread use of steel 45 in the production of various parts such as gears and crankshafts, which is typical in various branches of mechanical engineering. Prior to the supersonic arc metallization process, the samples were prepared by mechanical methods including grinding and sanding with silica sand. Sandblasting was carried out with a Nordberg NS3 device. The roughness of the samples after sandblasting was 2.3 μm. The coatings were sprayed using a SX-600 supersonic electric arc metallizer. Figure 1 shows a general view and schematic of this unit. The SX-600 includes a power supply, supersonic arc atomizer, control system, and compressed air system. The parameters of supersonic arc metallization are presented in Table 2.

Methods for studying the structural-phase state of a coating

An X'PertPRO X-ray diffractometer (Philips Corporation, Amsterdam, The Netherlands) using Cu-Kα radiation (λ = 1,5406 Å) was used to analyze the phase composition of the coatings. The diffractograms were analyzed using HighScore software in the angle range 20–90° with a step size of 0.02 and a counting time of 0.5 s/step. The porosity of the coatings was measured using ImageJ program [12] on cross-sectional images of the coatings obtained using a JSM-6390 LV JEOL scanning electron microscope.

Methods for studying mechanical and tribological properties

The roughness of the coatings was measured using a HY2300 Anytester profilometer. The

Table 1. Chemical composition of 30HGSA grade steel

C, %	Mn, %	Si, %	S, %	P, %	Cr, %	Ni, %
0.25–0.35	0.8–1.2	0.8–1.2	≤ 0.025	≤ 0.025	0.8–1.2	≤ 0.4

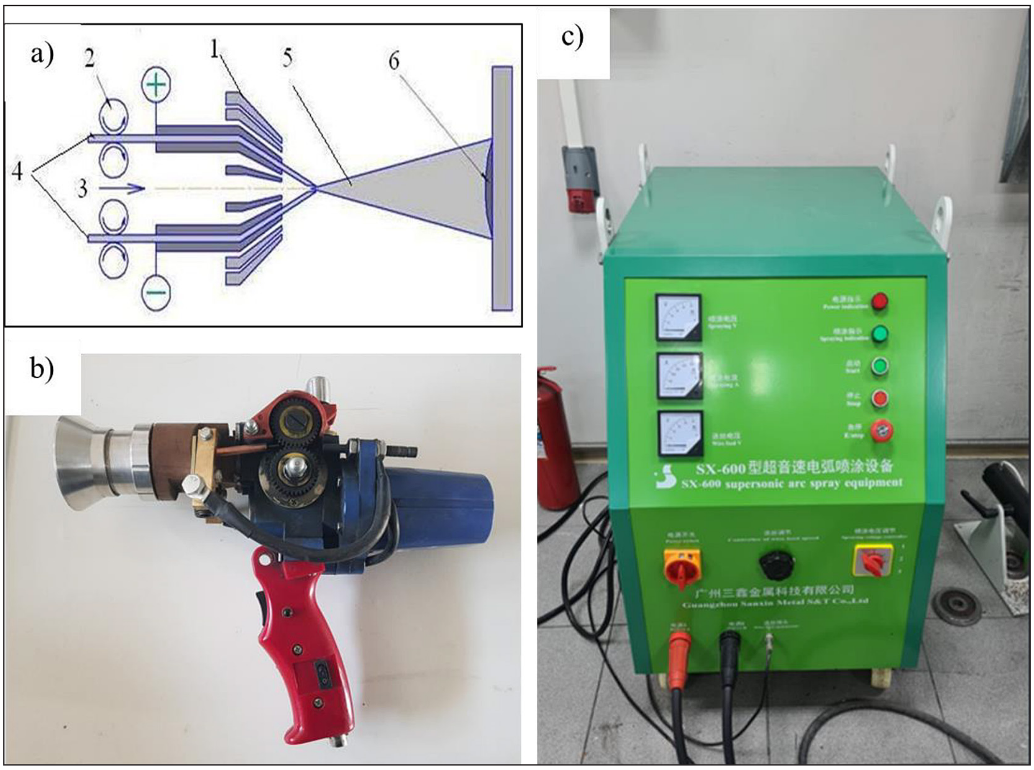

Figure 1. (a) Technological scheme of SX-600 (1 – metallizer body; 2 – wire feeding mechanism; 3 – air supply channel; 4 – electrode wires; 5 – electric arc with sprayed wire particles; 6 – sprayed coating) (b) appearance of the gun c) appearance of the source

Table 2. Regimes of 30HGSA coatings deposition by supersonic arc metallization

Sample	Voltage, V	Current, A	Wire feed speed, cm/s	Compressed air pressure, atm	Spraying distance, mm	Spraying time, s
No. 1	32	95	4	8	150	15
No. 2	38	95	4			
No. 3	44	95	4			

microhardness of the created coatings was determined from the cross section using a Vickers HLV-1DT microhardness tester with an indenter load P = 2H and a holding time at this load of 10 seconds. Tribological sliding friction tests were carried out on a TRB3 tribometer (Anton Paar Srl, Pezo, Switzerland) using the standard ball-disc technique (ASTM G 99) [154] (Fig. 2). A ball with a diameter of 3.0 mm made of steel 100X6 (analogous to ШХ15) was used as a counterbody. The tests were carried out at a load of 10 N, a linear speed of 5 cm/sec, a wear radius of curvature of 1.5 mm and a sliding distance of 100 m. Before tribological testing, all samples were ground on a grinding machine using 240p paper. The tribological characteristics of the coatings were characterized by wear intensity and friction coefficient.

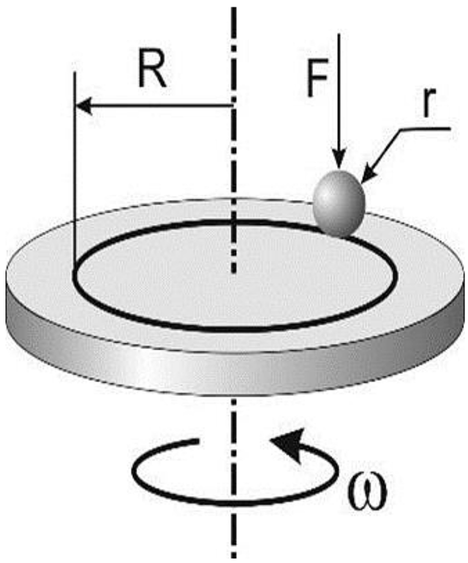

Figure 2. Tribological tests of samples using the "ball-disc" scheme

Methods for studying corrosion properties

An electrolytic cell with Potentiostat cs300m potentiostat was used to evaluate the corrosion resistance of the coatings. The measurements were carried out in 3.5% NaCl solution using a three-electrode scheme: the coating sprayed by EAM method to 45 grade steel served as a working electrode, the chlorosilver electrode was a reference electrode, and the platinum electrode was an auxiliary electrode, scanning speed 0.5 mV/s, surface area 1 cm^2, stabilization time 1 hour, EOC range: initial E(V): -0.1 vs. OCP, final E(V): 0.1 vs. OCP.

Method for testing the adhesive strength of coatings

The adhesive strength of the coatings was determined using the pin method using a WDW-100kN universal tensile testing machine. The essence of this method is to establish the magnitude of the destructive force when pulling the pin in the direction normal to its end surface, on which the coating is applied. The sample (see Fig. 3) consists of a pin and a substrate, equipped with a gripping device in the form of a hole and a fastening element for fixing the pin. Five samples of each type were prepared for this test. The shape of the substrates was made circular so that the pin hole was located exactly in the center of each sample.

RESULTS AND DISCUSSION

Results of SEM images of cross sections

The images presented in Figure 4, obtained using a scanning electron microscope (SEM), demonstrate coatings made by supersonic supersonic arc metallization. The bottom of each image is the substrate and the top is the applied coating.

The cross-sectional scanning electron microscope (SEM) images obtained in Figure 4a, b, c show that the coating thickness of samples No. 1 and No. 2 is higher than that of sample No. 3. This indicates the stability of the coating process under these conditions. The thickness measurement results are shown in Table 3.

In sample No. 1, the coating is dense and adheres well to the substrate, although the interface between the coating and the substrate is still visible, although not very noticeable. The pores at the interface between the substrate and coatings are small and rare, which indicates a high-quality coating application. In sample No. 2 the coating is also dense and uniform. The interface between the coating and the substrate is minimal, indicating better adhesion of the coating to the substrate compared to other samples. In sample No. 3, the coating is less dense and uniform, with larger and more noticeable pores at the interface. The interface boundaries are more pronounced and uneven, which may indicate poorer adhesion of the

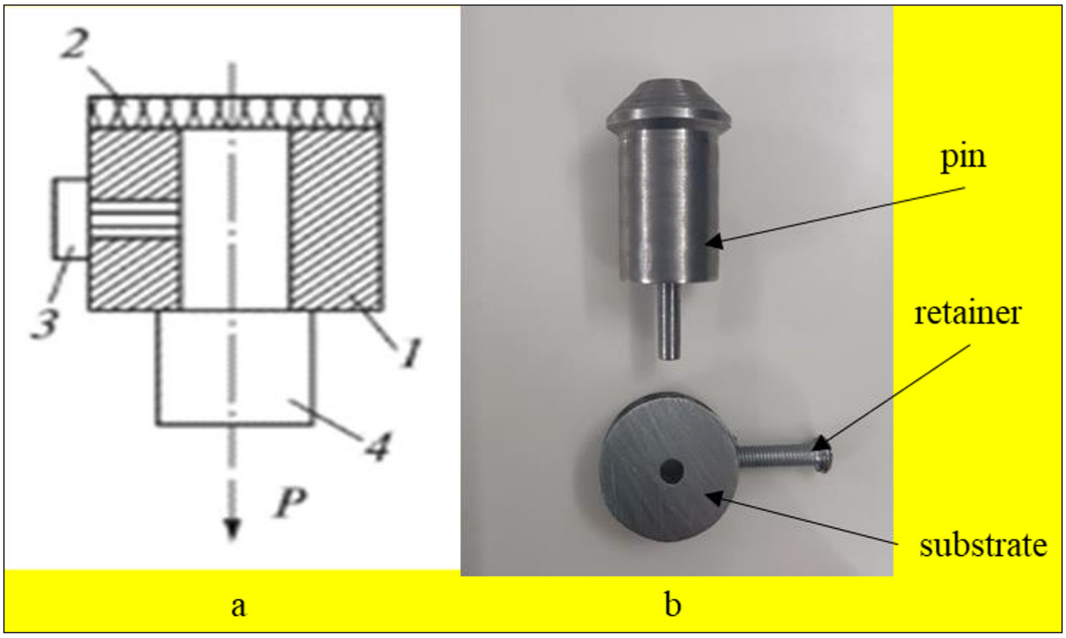

Figure 3. Tests on adhesion strengths of coatings by the pin method. (a) scheme of the prepared sample: 1 – substrate (steel 45); 2 – coating; 3 – retainer; 4 – pin (b) general view

Table 3. Coating thickness

Sample	No. 1	No. 2	No. 3
Thickness, μm	610.76 ± 27.68	661.85 ± 14.32	373.53 ± 33.04

coating to the substrate. This may indicate that with high voltage and slow wire feed, the likelihood of poor coating adhesion to the substrate increases (Figure 4d, e, f). This can negatively affect the mechanical strength and durability of the coating in use.

These differences in coating structure and interfaces can significantly influence functional characteristics such as wear and corrosion resistance. Denser, more uniform coatings with minimal porosity and fine interfaces are generally preferred for better performance.

Roughness test results

The image in Figure 5 shows the surface roughness of the coatings after supersonic arc metallization (EAM). The parameter Ra, which is

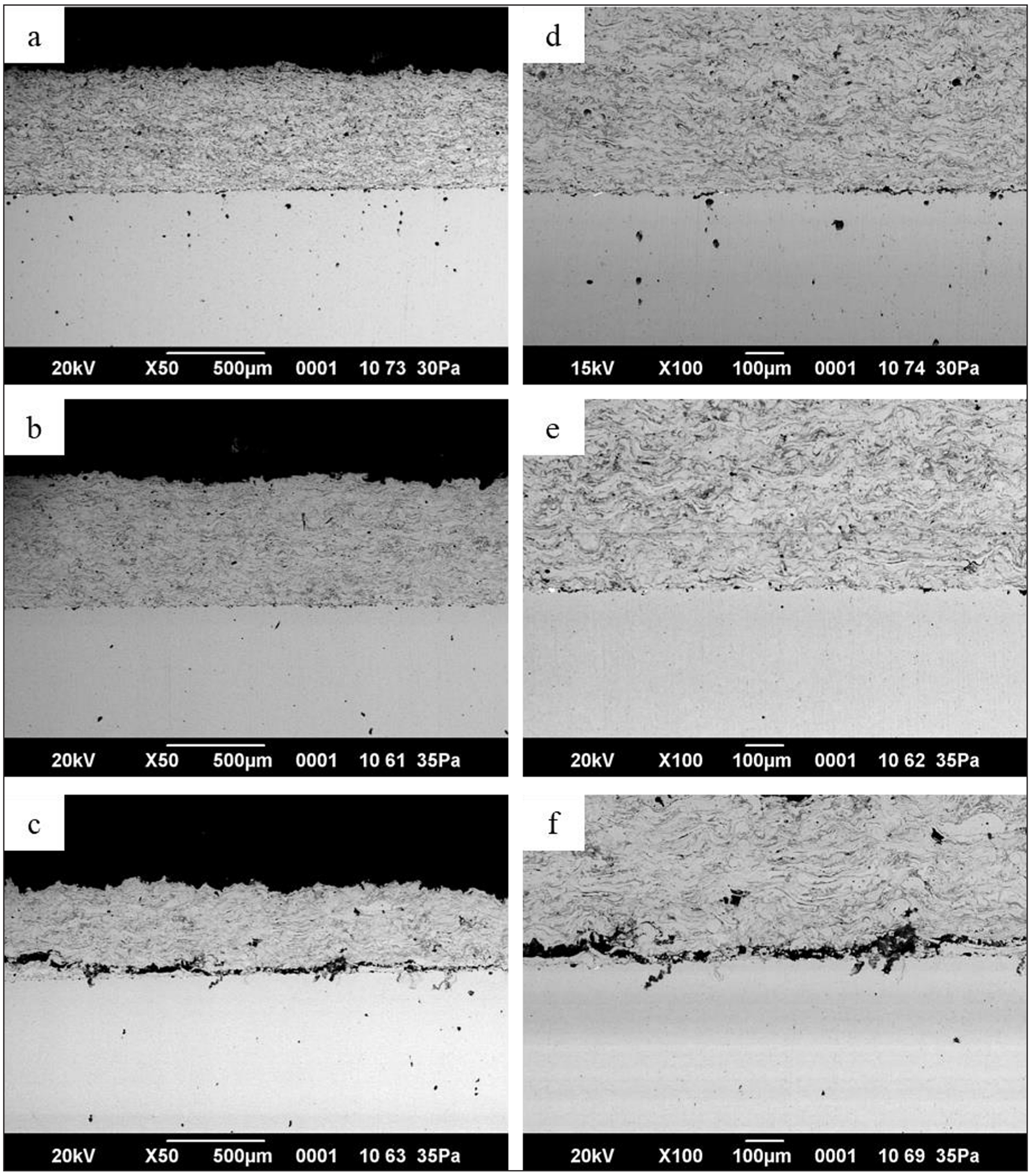

Figure 4. SEM images of cross sections of samples at different magnifications: x50 – (a) No. 1, (b) No. 2, (c) No. 3; x500 – (d) No. 1, (e) No. 2, (f) No. 3

the arithmetic mean deviation of the surface profile, was chosen to evaluate the roughness. From the presented images, it can be seen that increasing the voltage does not always lead to a decrease in roughness. For example, sample No.1 is characterized by a large number of shear particles and its Ra value is 11.2373, while for samples No. 2 and No. 3 this value is 8.0352 and 9.5912, respectively (Table 4).

Voltage plays a key role in the supersonic arc metallization process as it affects the stability and intensity of the arc. At optimum voltage, the arc becomes stable, which promotes uniform metal atomization and quality coating formation. Too low a voltage can led to an unstable and intermittent arc, resulting in uneven coating. In contrast, too high a voltage can cause excessive metal spraying and increased coating roughness [14–17].

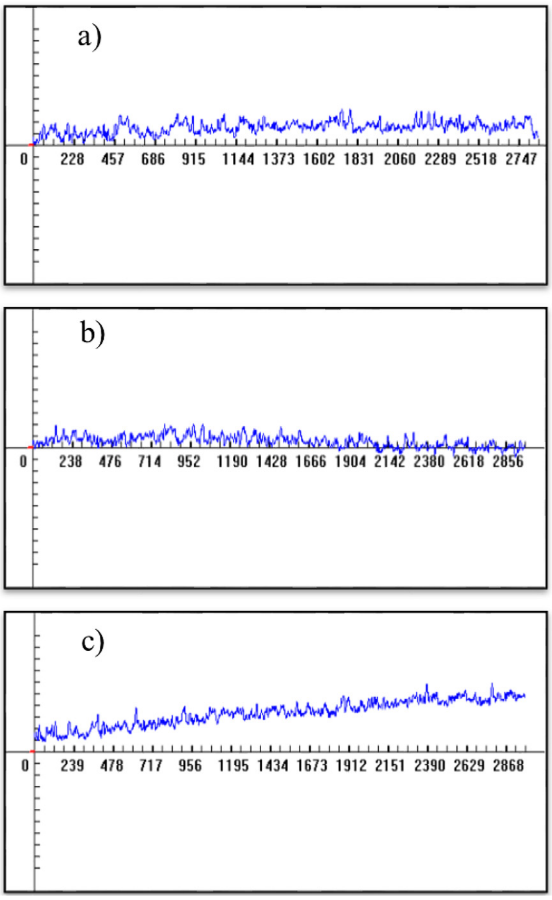

Figure 5. Results of roughness measurement of coatings: (a) No.1; (b) No.2; (c) No.3.

Results of X-ray diffraction analysis

Figure 6 shows the results of X-ray diffraction analysis, which confirm the presence of iron oxide (FeO) and alpha iron (α-Fe) in the coatings. Iron oxide FeO, characterized by stability at high temperatures, remains in its phase due to rapid cooling, which allows it to remain in phase at room temperature. Additionally, FeO is known as an effective solid lubricant due to its crystalline structure and chemical composition, which provides applications in various industrial applications [18–24].

Changes in the intensity of the peaks in the diffraction patterns indicate the influence of voltage on the phase composition of the coating. For example, sample No. 2 shows an iron oxide (FeO) content of 42.9% and alpha iron (α-Fe) of 57.1%, indicating an increase in the oxide phase due to a decrease in the metallic phase. This change is especially noticeable with increasing voltage, which leads to increased oxidation of the material. For sample No. 3, the proportion of iron oxide reaches 45.9%, while alpha iron decreases to 54.1%. This trend supports the theory that increased voltage increases oxidative processes.

These results highlight the importance of controlling process parameters, including voltage, to achieve optimal phase composition and properties of coatings. Controlling these parameters allows you to tailor the properties of coatings for specific applications, improving their wear resistance and corrosion resistance.

Vickers hardness test results

The hardness of coatings produced by supersonic arc metallization depends on several factors, including the material used for coating, the application process, and the working conditions. For example, the hardness of the 30HGSA steel wire is significantly higher than that of the steel 45 material at 286 HV. As shown in Figure 7 in samples No. 1 and No. 2, the increase in the hardness of coatings after supersonic arc metallization is due to the fact that at the moment of contact with the substrate, metal particles are subjected to sharp cooling due to a cold jet of compressed

Table 4. Roughness of coatings obtained by supersonic arc metallization

Sample	No. 1	No. 2	No. 3
Roughness Ra, µm	11.2373 ± 0.77	8.0352 ± 0.24	9.5912 ± 0.51

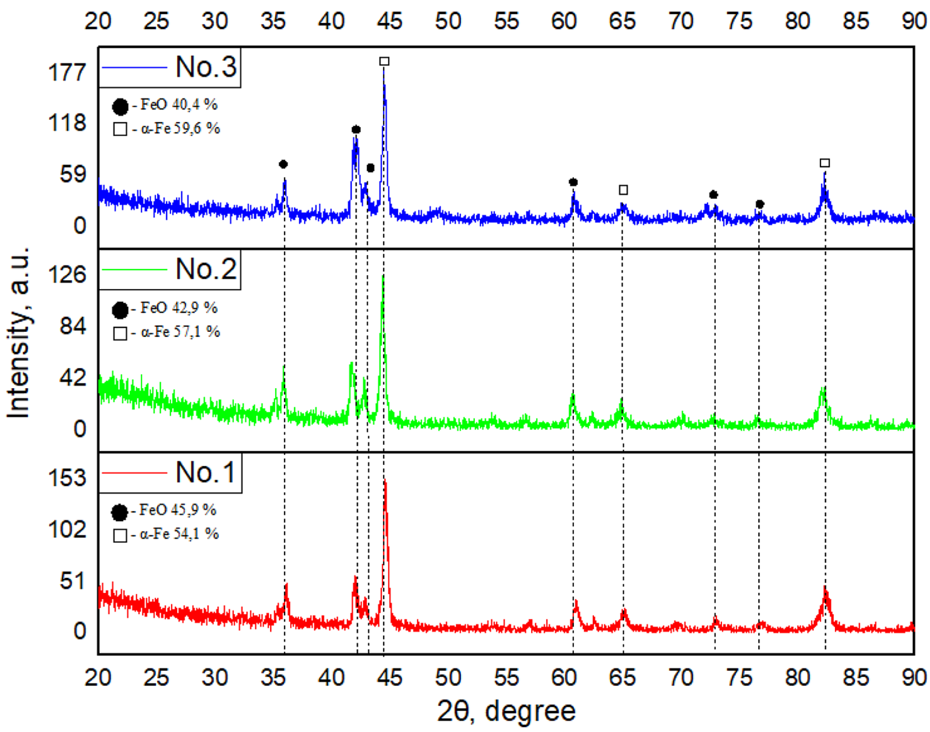

Figure 6. X-ray diffraction analysis results

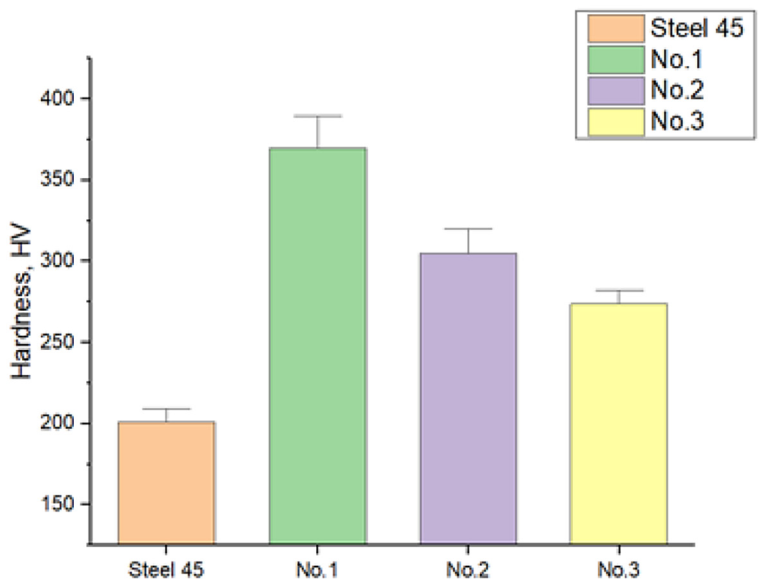

Figure 7. Microhardness test results

air, which contributes to their instant hardening. However, in the case of sample No. 3, too high a voltage can led to excessive sprayed and oxidation of the metal. Since sprayed and oxidation of the metal have a negative effect on its hardness. [19, 20]. These observations highlight the importance of voltage control during the supersonic arc metallization process to achieve optimum hardness and coating quality.

Porosity study results

The porosity results presented in Figure 8 and Table 5 confirm that the percentage of porosity of the coatings decreases with increasing voltage. This is especially noticeable in the case of sample No. 2, which has the smallest average pore size compared to the other samples. This is due to the fact that increase in voltage leads to increase in current

Table 5. Porosity values of the obtained coatings

Sample	Average pore size, μm	Percentage of porosity, %
No. 1	36.590	2.553
No. 2	28.057	1.806
No. 3	55.938	1.727

strength, which in turn increases the heat energy release in the electric arc to melt the wire. Such a process favors the formation of dense coatings with minimal porosity. On the other hand, in the case of sample No. 3, where a higher voltage is applied than that of samples No. 1 and No. 2, the porosity results are not so favorable. This may be due to the fact that high voltage with relatively slow wire feed (improperly selected voltage) can lead to increased porosity and non-uniformity of the coating, which reduces its wear resistance. Optimal voltage combined with the correct wire feed speed promotes the formation of a uniform and dense coating, which in turn improves its wear resistance.

Wear resistance results

Supersonic arc metallization additionally, wear marks resulting from the tribological tests are visible in Figure 9. Sample No. (Figure 10b) shows significant wear, characterized by a long and deep scratch, indicating aggressive wear conditions and significant material removal. While the smoother surface of sample No. 2 (Figure 10c)

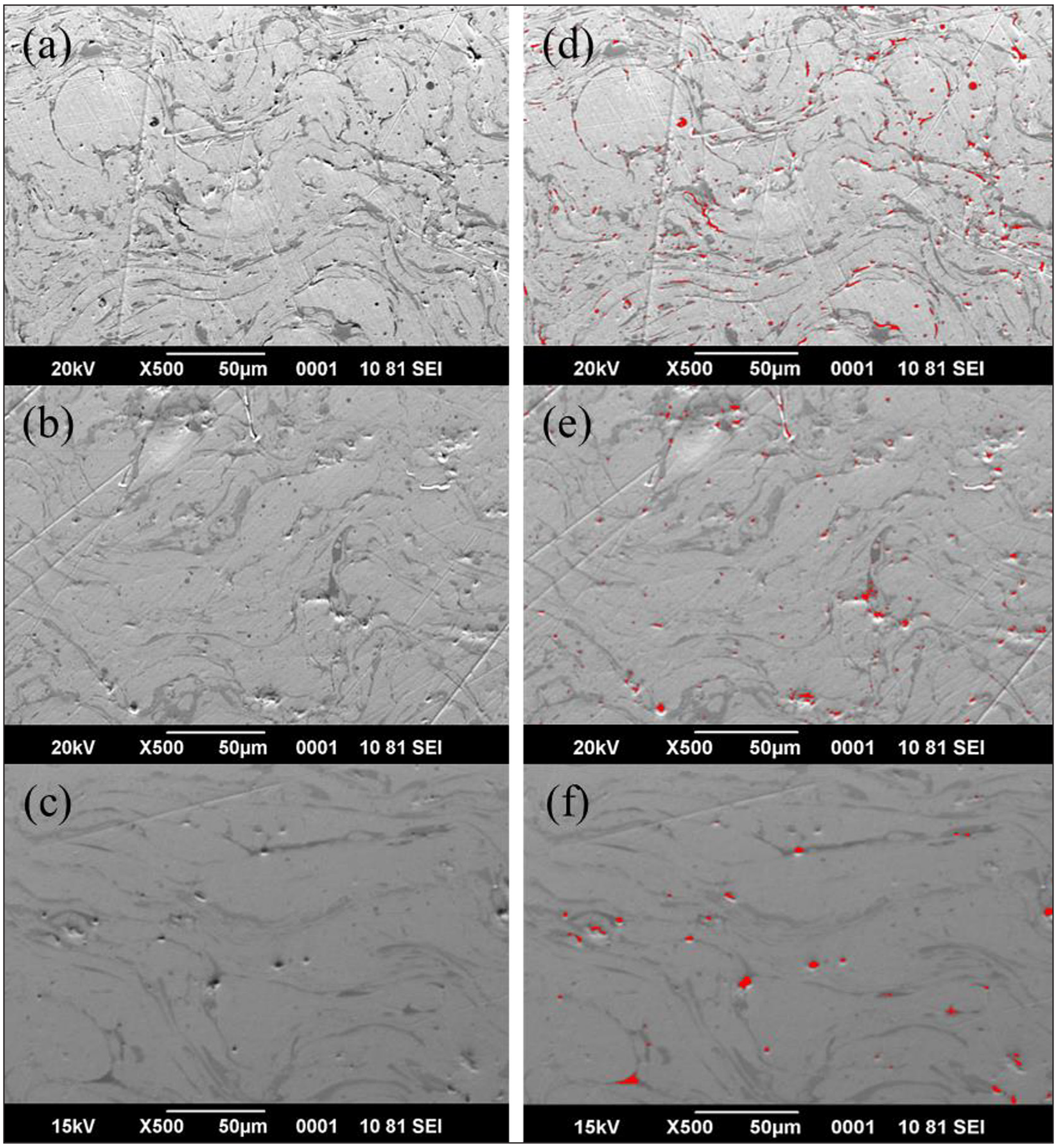

Figure 8. Microstructure of cross sections of coatings at a magnification of x500: (a) No. 1, (b) No. 2, (c) No. 3 and images of micropores obtained using the ImageJ software package: (d) No. 1, (e) No. 2, (f) No. 3.

with little wear indicates its increased strength and durability of the coating. Sample No. 3 (Figure 10d) shows wear marks in a diffuse, mottled pattern, suggesting more evenly distributed wear due to abrasive particles. These observations help evaluate the durability of coatings and surface finishes under simulated test conditions and actual use, highlighting the importance of selecting optimal parameters for each application.

Corrosion resistance research results

The corrosion test results of the coatings are presented in Table 6. These results show an improvement in the corrosion resistance of the samples after the supersonic arc metallization process. Corrosion is one of the main causes of degradation of materials, especially equipment and structures exposed to the environment. Figure 11 shows a plot of corrosion potential versus current density. It uses a logarithmic scale for the current density on the horizontal axis, which allows to see the behavior over a large range of current values. Coating defects such as pores and cracks have a negative effect on corrosion properties. They are pathways for the penetration of aggressive media and their amount in the coating microstructure should be minimized. Studies show that the dense and homogeneous coating structure

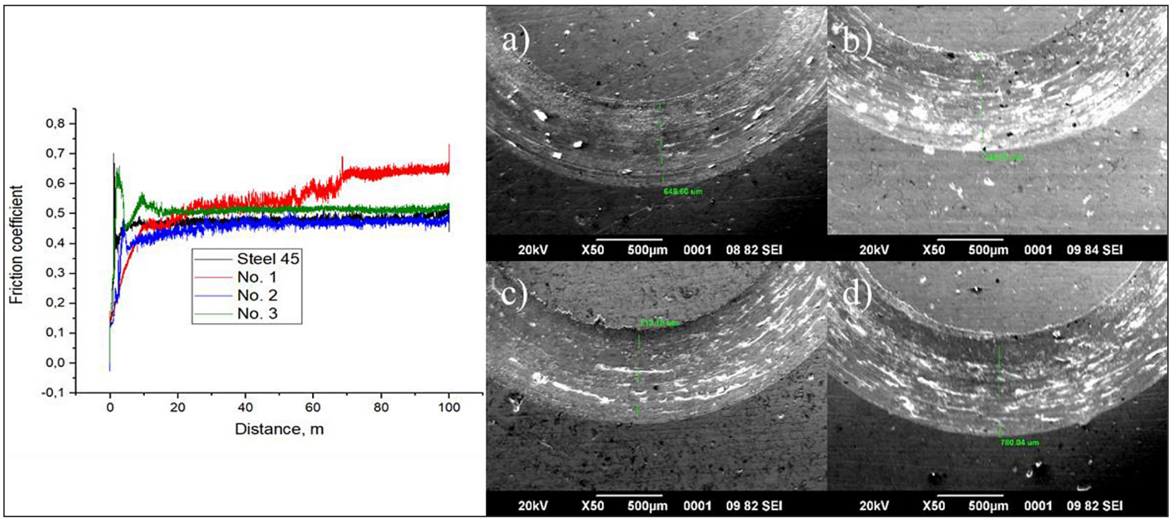

Figure 9. Tribological test results: (a) initial, (b) No. 1, (c) No. 2, (d) No. 3.

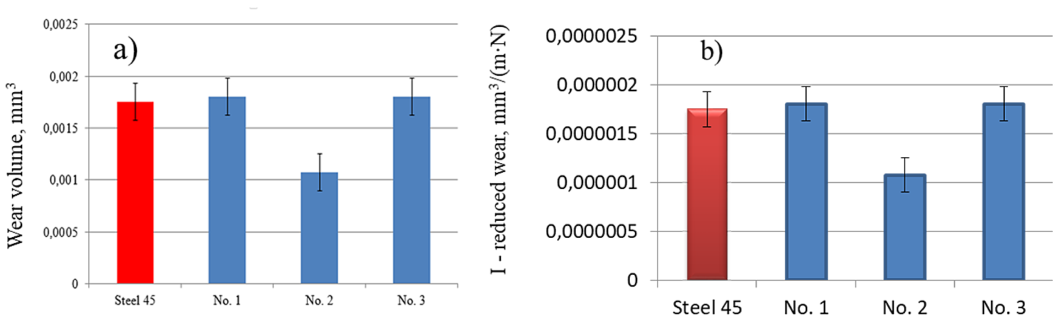

Figure 10. Results of tribological tests (a) wear volume (b) reduced wear

Table 6. Results of calculating the corrosion parameters of the samples

Sample	Corrosion current $I_к$, μA/cm^2	Free corrosion potential $E_к$, V	Corrosion rate, mm/year
Steel 45	1.6481E-05	-0.45487	0.19334
No. 1	7.9263E-0.6	-0.3618	0.092985
No. 2	7.987E-06	-0.36789	0.093697
No. 3	1.6358E-05	-0.38998	0.1919

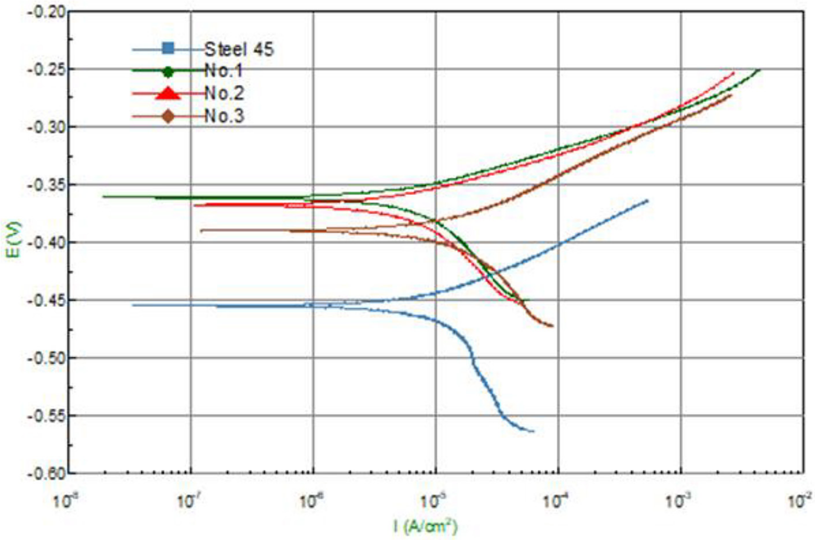

Figure 11. Polarization curves obtained from electrochemical corrosion tests of the samples

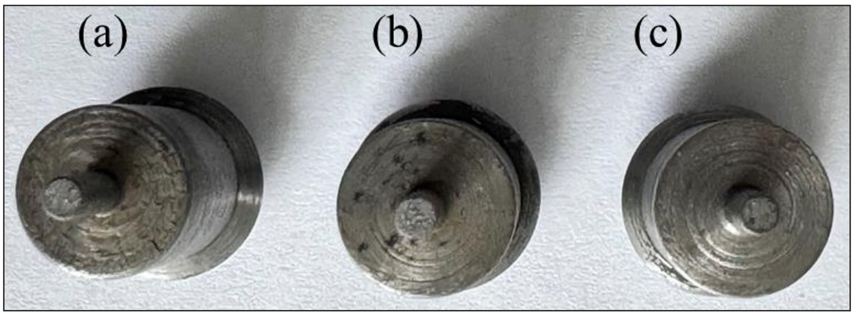

Figure 12. Images of the pin surface after testing the adhesive strength of coatings using the pin pullout method: (a) No. 1; (b) No. 2; (c) No. 3

of samples No. 1 and No. 2 helps to prevent the penetration of moisture and aggressive substances inside the coating, which in turn increases its corrosion resistance [24]. In contrast, sample No. 3 may have lower corrosion resistance due to less dense structure and presence of defects. Such pores and cracks can become entry points for moisture and corrosive agents, degrading the corrosion properties of the coating.

Results of a study of the adhesion strength of coatings

When testing the adhesive strength of coatings obtained by supersonic supersonic arc metallization using the pull-off test method, an adhesive fracture occurred in all samples, that is, the coating was torn off from the substrate. Figure 12 shows that there is no coating on the surface of the pin, that is, a clear interface has formed between the coating and the substrate. According to the data obtained during the adhesion strength tests, samples No. 1 and No. 2 demonstrate better adhesive properties, as shown in Table 5. Voltage plays an important role in the adhesion strength of coatings to the substrate during supersonic supersonic arc metallization. Optimal tension contributes to the formation of a high-quality coating with good adhesion to the substrate. Too low a voltage can cause arc instability and consequently poor adhesion. On the contrary, too high a voltage can lead to excessive spattering of the metal and an increase in the porosity of the coating, which will also negatively affect the strength of the joint [19, 20].

Table 7. Test results of adhesion strength of coatings

Samples	Coating bond strength, MPa
No. 1	17.5 ± 1.21
No. 2	19.74 ± 0.75
No. 3	8.28 ± 2.45

CONCLUSIONS

Based on the above results, the following conclusions can be drawn. The study emphasized that voltage plays a significant role in the process of supersonic arc metallization, affecting the stability and intensity of the arc, which in turn affects the uniformity and quality of the coating. Optimally selected voltage leads to the formation of dense and homogeneous coatings with good adhesion to the substrate and reduced porosis. X-ray diffraction analysis confirmed the presence of iron oxide FeO and alpha iron in the coating composition. It was found that with increasing voltage, the content of iron oxide increases. Such a change in voltage has a significant impact on the phase composition of coatings, which opens up opportunities for its targeted correction in order to optimize the properties of coatings depending on their specific operating conditions.

The variation in voltage during metallization was found to affect the wear resistance and corrosion properties of the coatings. Sample No. 2 with optimum voltage parameter shows better tribological and corrosion characteristics, which makes sample No. 2 more preferable for industrial applications.

The results of coating adhesion strength study by pinning method showed that sample No. 2 has better adhesion properties. This emphasizes the need for careful voltage control to ensure the adhesion strength of the coatings to the substrate, which is important for their durability and reliability in serve.

The study confirms that careful control of supersonic arc metallization process parameters, including voltage, is critical to ensure the desired properties of the coatings such as wear resistance, corrosion resistance and adhesion to the substrate.

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