

Influence of high-speed arc metallization wire feed rate on tribological and corrosion properties of 30HGSA steel coatings

Research Article

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Abstract: This study investigates the influence of wire feed rate on the porosity of coatings, elemental analysis, corrosion resistance, tribological properties, and microstructure of iron-based coatings deposited by high-speed arc metallization. The coatings were obtained using a SX-600 high-speed electric arc metallizer. The properties of Fe-based coatings depend on the arc-sputtering parameters. Determination of the optimum arc spraying parameters helps to minimize the deterioration of coating properties. Increasing the wire feed speed leads to an increase in the current value, which generates more heat energy in the arc to melt the wire and consequently favours the formation of dense coatings with low porosity. At high temperatures, Fe-based coatings form oxide deposits that protect the coating from further oxidation and increase coating hardness. Tribological tests show that the friction coefficient of coatings decreases in the presence of FeO on the coating surface, activating its self-lubricating ability. Investigation of the porosity of the samples showed that adjusting the wire feed affected both the pore size and the number of pores.

Keywords: Wire • Porosity • Coating • Arc metallization • Structure • Corrosion • Tribology

1. Introduction

One of the key tasks of modern engineering development is to increase the durability and reliability of machines. In most cases (85–90%), the cause of machine failure is wear and tear of parts. The costs for repair and restoration of machine parts are constantly increasing. Approximately one-third of the machine fleet is in repair enterprises, and metal consumption for the production of spare parts exceeds 20% of the annual smelting. Restoration of machine parts allows saving high-quality metal, fuel, energy, and labour resources, as well as contributes to the rational use of natural resources and environmental protection [1]. Restoration of worn parts requires 5–8 times less technological operations compared to the manufacture of new parts. In this regard, the development of technology for the restoration of machine parts is an extremely urgent task.

Among the various coating technologies [2], gas-thermal methods [3], such as plasma [4], gas flame [5], cold gas dynamics (CGD) [6], detonation sputtering (DS) [7], and electric arc metallization (EAM) [8], have recently been actively developed. The basic principle of these methods is the formation of a protective layer of discrete material particles heated and accelerated by a high-temperature gas jet. Low thermal impact on the base (usually heating up to 80–150°C) allows avoiding undesirable structural changes, deformations, and changes in the dimensions of parts.

The most economical method [9] among the above-mentioned is EAM, with energy efficiency up to 60–70% [10,11] and coating thickness up to 20 mm [12]. The process consists of applying voltage to two wires acting as electrodes. When they come together, an electric arc occurs, melting the wires. Compressed air captures the molten metal particles and accelerates them.

The study of the influence of different EAM modes on the surface restoration of steel machine parts is of great

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relevance. The results obtained can be used to optimize the EAM process parameters and to improve the efficiency and durability of the reconditioned machine parts, as well as to increase their mechanical properties. These findings have important applications in the automotive and industrial fields. Many studies have been devoted to investigating the influence of different deposition parameters on the characteristics of metallic coatings obtained using an arc. For example, Weis et al. [9] discussed the effect of deposition parameters on the characteristics of arc-deposited zinc coatings. The study showed that the properties of the resulting coatings, such as microstructure, porosity, and hardness, were closely related to the deposition process parameters. In another study [10], the authors optimized the process parameters such as current, voltage, sputtering distance, and gas pressure during the twin-wire arc plating of aluminium coating to achieve the desired microstructure and physical and mechanical properties.

Fe-based coatings have significant potential for anti-corrosion [11] and anti-wear applications [12]. They are also excellent candidates for use at medium and high temperatures due to their good oxidizing properties [13]. Fe-based coatings have high hardness [14] and resistance to mechanical damage [15], making them effective in high-friction [16] and mechanically stressed environments. The use of iron coatings and arc metallization technology can reduce the cost of protecting metal products [17] compared to more expensive materials such as nickel or chromium [18].

The aim of this article is to investigate the effect of wire feed rate on the corrosion and structural properties of coatings of 30 CHSA wire on the surface of 45 steel obtained by high-speed arc metallization.

2. Materials and methods

A 30 HGSA steel wire with a diameter of 1.6 mm was used as the material to be sprayed. The chemical composition of 30 HGSA steel is shown in Table 1. The coatings were applied to samples made of steel 45. The samples were made from a bar of steel 45 (according to GOST 1050-2013). The choice of this material is owing to its wide application in the production of various parts, such as

gears and crankshafts, which is typical for various branches of mechanical engineering. Before the process of EAM the samples were preliminarily prepared by mechanical methods, including grinding and sandblasting with quartz sand.

Coatings were obtained using a high-speed electric arc metallizer SX-600. Figure 1 shows the general view and schematic of the SX-600 supersonic metallization unit. This unit includes a power supply, supersonic arc atomizer, control system, and compressed air supply system.

A high-speed arc spraying machine directs two atomizing metal wires to two electric atomizer nozzles, and the electric nozzles are connected to two high-current and low-voltage electrodes. When the two metal wires come in contact with each other, a short circuit will occur, which can cause an arc, and the metal wire will be melted by the heat generated by the arc. The molten wire is then pulverized to microparticles by high-speed compressed air. These microparticles are then atomized onto the surface of the workpiece with compressed air at supersonic speed (over 400 m/s) to form a coating. Compared to conventional arc spraying, supersonic spray coating has a smaller and more compact microstructure and stronger bonding force (Table 2).

Elemental analysis and cross-sectional images of the samples were obtained on a Tescan Mira3 scanning electron microscope. The corrosion resistance of the coatings was studied in an electrolytic cell using a potentiostat cs300m. The measurements were carried out in 3% NaCl solution using a three-electrode scheme: the working electrode was the coating applied from EAM to steel 45, the role of the reference electrode was played by a chloro-silver electrode, and the platinum electrode served as an auxiliary electrode. Corrosion currents were determined by extrapolating the linear parts of the polarization curves to the corrosion potential. The ImageJ program [19] was used to measure the porosity of the coatings using cross-sectional images of EAM coatings taken on the JSM-6390 LVJEOL SEM [20]. The phase composition of the coatings was studied using an X-ray diffractometer (X'PertPRO, Philips Corporation, Amsterdam, Netherlands) with Cu-K α radiation ($\lambda = 2.2897 \text{ \AA}$). The diffractograms were decoded using the HighScore program, and measurements were made in the 2θ range of 20° – 90° , with a step of 0.02 and a counting time of 0.5 s/step . Microhardness of the cross-

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

Table 1. Chemical composition of 30HGSA grade steel.

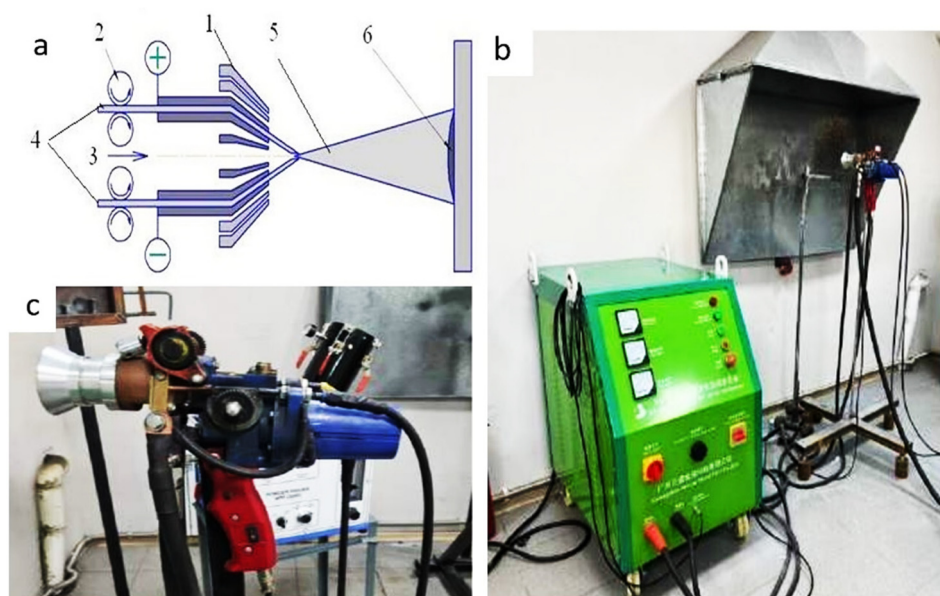


Figure 1. (a) Technological scheme of SX-600 (1 – metallizer body; 2 – wire feeding mechanism; 3 – air supply channel; 4 – electrode wires; 5 – electric arc with sprayed wire particles; 6 – sprayed coating), (b) appearance of the gun, and (c) appearance of the supersonic EAM complex.

section of the samples was measured in accordance with GOST 9450-76 (ASTM E384-11) on a micro hardness tester Metolab 502, at indenter loads $P = 1$ N and dwell time 10 s. Tribological tests on sliding friction were carried out on tribometer TRB3 (Anton Paar Srl, Peseux, Switzerland) using the standard method “ball-on-disk” (international standards ASTM G 133-95 and ASTM G99), whereas a countersample used a ball with a diameter of 6.0 mm, made of steel Shx15, at a load of 5 N, and a friction path of 100 m.

Electrochemical measurements were used to experiment on the corrosion resistance of the samples under study. Galvanic corrosion testing was carried out using a CS300M potentiostat/galvanostat. Using three different cables, reference electrode RE (calomel electrode), auxiliary electrode CE (platinum electrode), and working electrode WE (sample), the potentiostat is connected to the electrochemical cell to measure the corrosion rate as a function of the potential at the working electrode (Figure 2). The area of the tested samples was 1 cm^2 . The corrosion test medium

used was a 0.5 M NaCl solution, which was divided into separate containers that were electrically connected via a salt bridge.

3. Results and discussion

Figure 2 shows the cross-sectional microstructures and elemental analysis results of the coatings obtained at different wire feed rates. The results showed that at different spraying modes, all coatings are dense with a pronounced lamellar structure. This type of structure is characteristic of coatings formed from particles that are in a liquid state at the moment of impact with the substrate and have a sufficiently high velocity. In the SEM image, the entire coating has a lamellar structure consisting of grey, dark grey, and dark-coloured areas. Previous studies have shown that the grey, dark grey, and dark-coloured regions represent iron, oxides, and pores, respectively [21,22]. The result

Sample	Voltage (V)	Current (A)	Wire feed speed (cm/s)	Compressed air pressure (atm)	Spraying distance (mm)	Number of samples
No. 1	43	100	4	8	150	3
No. 2		200	8			3
No. 3		300	16			3

Table 2. Regimes of 30HGSA coating application by EAM.

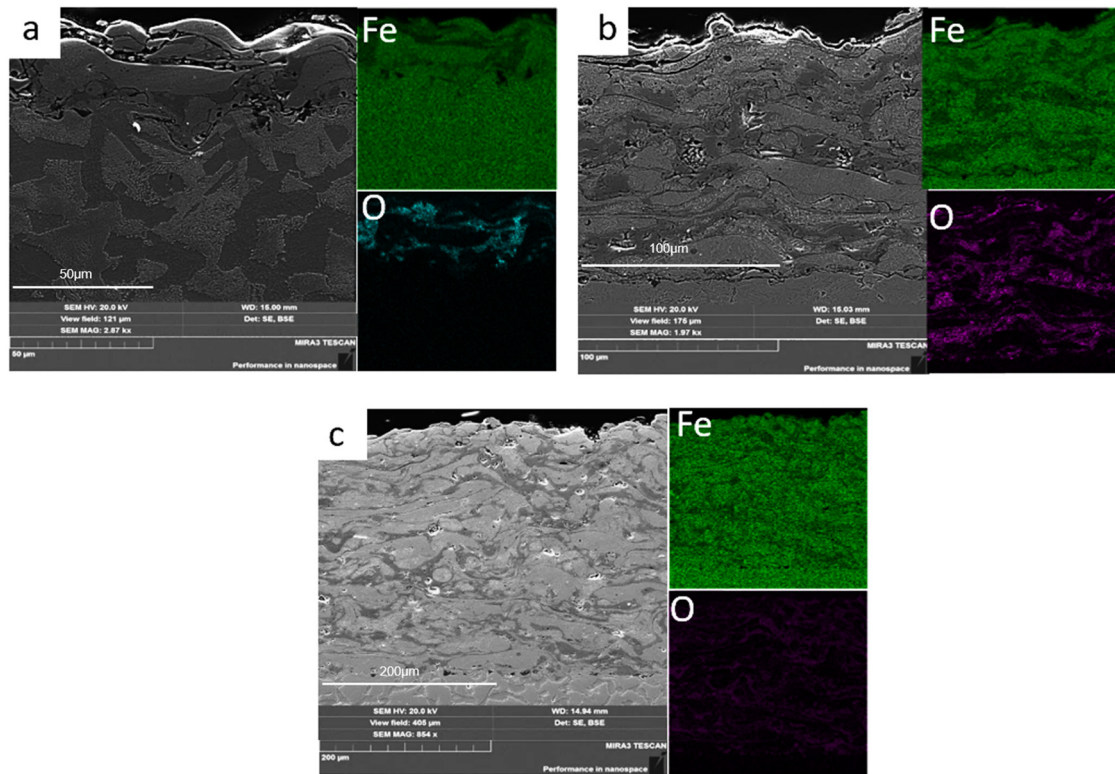


Figure 2. Microstructure and elemental analysis of coatings: (a) No. 1, (b) No. 2, and (c) No. 3.

of the EDS analysis confirmed that the coating is composed of Fe, iron oxides, and pores. This is a typical microstructure of iron coating produced by super arc sputtering. The oxides are present in a variety of structures, including thin layers of oxide distributed between the iron droplets, spherically shaped oxide particles found within the iron droplets, and large pieces of oxides, including small spherical iron particles. A large amount of oxides can be observed in coating No. 2 compared to other coatings. The peculiarities of oxide distribution are attributed to turbulent mixing due to toroidal flow in flying particles during atomization [21,23]. In Figure 2, the thickness of the coatings can be seen to increase with increasing wire feed speed.

Figure 3 shows the results of X-ray diffraction analysis, which confirm that the oxide in the coating is FeO. Since compressed air is used as the atomizing gas, the iron in the alloy interacts with the oxygen in this gas to form FeO (wustite), a high-temperature oxide that solidifies at room temperature due to the high cooling rate. Wustite is a solid oxide phase that acts as a solid lubricant and provides good tribological properties to the coating. One of the many iron oxides, FeO, remains stable at high temperatures, but rapid cooling can achieve its retention in phase at low temperatures. In addition, as mentioned, FeO is

known as an effective solid lubricant due to its crystal structure and lattice chemical nature [21]. When changing the wire feed speed, it can be noticed that the intensity of peaks changes. In coating No. 2, a significant decrease in bcc-Fe peaks and an increase in FeO peaks can be observed. FeO can increase the wear resistance by increasing the hardness or the role of a solid lubricant [22,24].

Figure 4 shows the surface morphology and surface roughness measurements of the coatings after EAM. The results show that during the flight of liquid metal particles, depending on the magnitude of surface tension forces, their flight speed and metallization distance acquire a spherical drop or fragment shape. When colliding with the substrate, the metal particles deform and partially splatter. The shape of the flattened metal particles constituting the coating allows us to conclude that at the moment of impact they are in a plastic and round state in which they are easily deformed. It was found that large metal particles reach the surface predominantly in the liquid state and smaller ones in the plastic and even solid state. In this case, regardless of the size, metal particles that are in the centre of the air jet cool insignificantly and at the periphery – more vigorously. Therefore, the metal particles that make up the coating reach the substrate in a

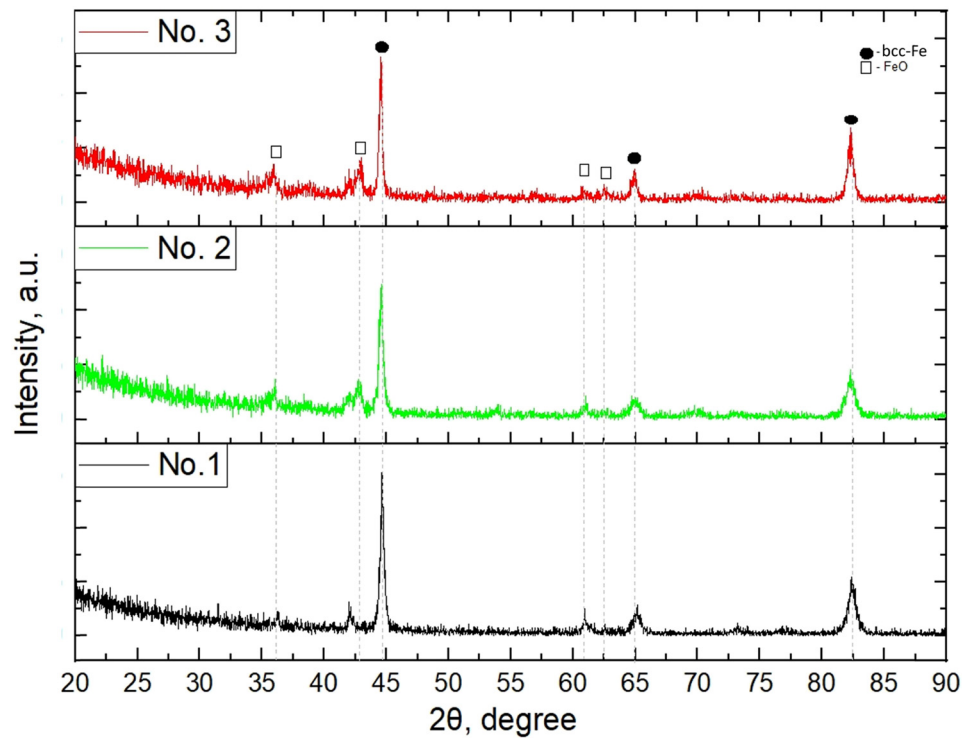


Figure 3. Results of X-ray diffraction analysis: No. 1, No. 2, and No. 3.

different state. The predominant number of them is in a liquid or semi-liquid (plastic) state, and only a small part is in the solidified state. Due to the kinetic energy of the metal particles flying at supersonic speed, when hitting the substrate, the surrounding shell is destroyed, and the liquid metal wets the surface and, filling the irregularities, tightly contacts it. Cooler metal particles are deformed on impact, flattened and, mixing with hotter particles, form a

single coating layer. From the obtained images, it can be observed that with increasing wire feed (increasing current), the particle size decreases, and also, with increasing current, the density of the coatings is better. Sample No. 1 has more cut particles because the wire feed rate of this sample is four times less than that of sample No. 3. As the wire feed increases, the current increases, which leads to a reduction in particle size. By reducing the particle size, the

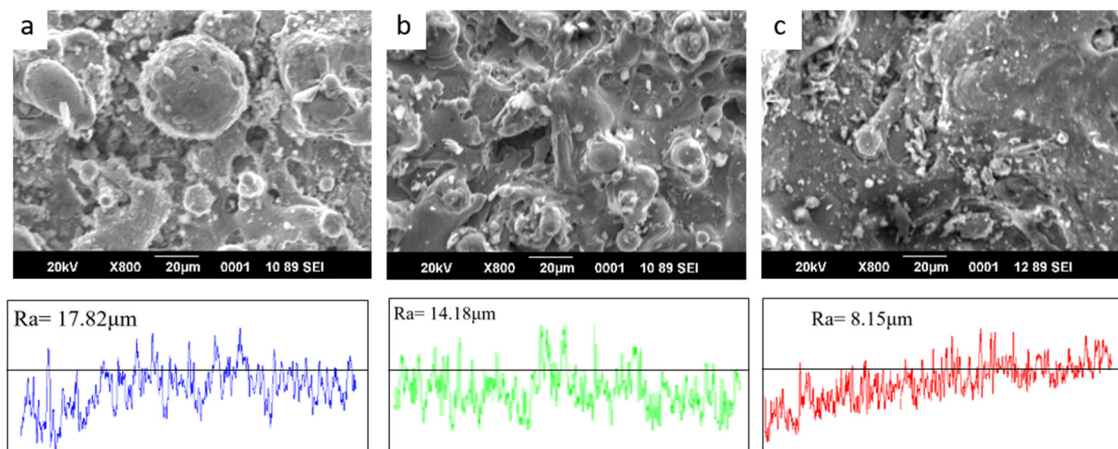


Figure 4. Surface morphology and roughness measurement results of coatings: (a) No. 1, (b) No. 2, and (c) No. 3.

coatings become more dense. The decrease in particle size also leads to a decrease in roughness. The Ra value, which is the arithmetic mean deviation of the profile, was chosen as the main parameter for evaluating the surface roughness of the coating.

The results of the porosity measurement are shown in Figure 5. As mentioned above, as the wire feed increases, the pore size also decreases. The porosity values are shown in Table 3. As shown in Figure 5c, sample No. 3 has the smallest number of pores in contrast to the rest of the samples. This is probably due to the fact that as the wire feed rate increases, the amperage increases, which leads to an increase in the heat energy released in the electric arc to melt the wire. This process contributes to the formation of dense coatings with minimal porosity. Sample No. 1 has increased porosity in contrast to other samples. This is probably due to the reduced wire feed rate. This wire feed rate may not be enough material to evenly coat the surface. This may result in voids and pores in the coating.

The hardness of a coating is one of the important characteristics that determine its operational capabilities. The operating conditions of machine parts for various purposes require an appropriate hardness of the product surface. For example, high-hardness coatings are used in the restoration of such heavily loaded parts as engine crankshafts, roll journals of rolling mills, railway car axles, rotor shafts of deep-well pumps, etc. At EAM, the hardness of the metal coating depends on the filler material (wire). It is possible to obtain coatings with different hardnesses on the same material. This study shows that the hardness of EAM coatings can be increased by changing the wire feed rate. The surface microhardness of the coating samples is shown in Figure 6. The microhardness of the coating significantly exceeds the hardness of the material of steel 45 and is 260–290 HV_{0.2}. The increase in hardness of the coating is explained by the fact that when striking the substrate, the metal particles are subjected to simultaneous deformation

Sample	Average pore size (nm)	Porosity percentage (%)
No. 1	45.474	2.536
No. 2	20.028	1.776
No. 3	19.060	1.018

Table 3. Porosity values of the obtained coatings.

and sharp cooling by a cold jet of compressed air, which leads to instantaneous hardening. In coating No. 2, a significant increase in hardness is observed due to the increase in the proportion of FeO, which may increase the hardness in the role of solid lubricant. In this regard, the reason for the different aspects of hardness change depending on the current strength is the dominant effect of oxidation degree change.

The results of the corrosion test of the coatings are shown in Figure 7. The results show an increase in the corrosion resistance of the samples after EAM. Coating defects such as pores and cracks have an unfavourable effect on corrosion properties. They act as passageways for corrosive media and their amount in the coating microstructure should be minimized [22]. Pores can create channels for aggressive media such as water, acids, or salts to penetrate the substrate. This leads to the initiation of corrosion processes where the substrate comes into contact with these media. The more pores there are in a coating, the greater the likelihood of corrosion. Therefore, sample No. 1 is characterized by lower corrosion resistance in contrast to sample Nos 2 and 3. The dense and homogeneous coating structure in sample No. 3 helps to prevent moisture and corrosive media from penetrating inside the coating, which increases corrosion resistance. The data of the coating corrosion test are presented in Table 4.

Figure 8a shows the friction coefficients of all coatings. Specifically, the coefficient of friction of all coatings ranged from 0.49 to 0.53. The results indicate that sample No. 2,

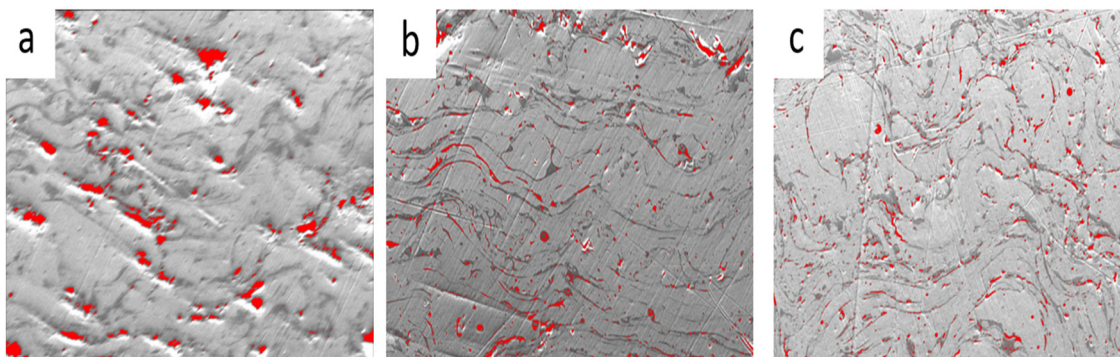


Figure 5. Images of micropores obtained using ImageJ software package: (a) No. 1, (b) No. 2, and (c) No. 3.

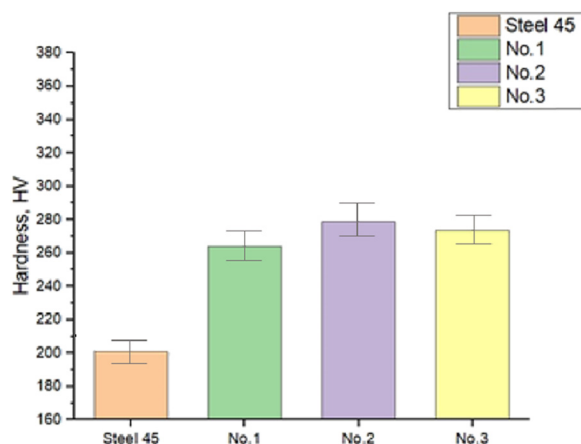


Figure 6. Results of hardness measurement: No. 1, No. 2, and No. 3.

with higher oxide content, has a lower coefficient of friction. Apparently, this effect is due to the presence of FeO on the coating surface, which activates its self-lubrication ability even under limited lubrication conditions. The results of the wear volume analysis are shown in Figure 8b. The higher the hardness and oxide content of the coating, the lower the wear volume of the coating. In the study of Lin et al. [22], FeO also had a significant effect on wear resistance due to its hardness and lubricating properties.

The SEM images in Figure 9 show the morphology of the worn surfaces of the coatings. Craters were observed on the worn surface of all coating samples. The image shows a distinct circular trail left by the ball. Light areas within the trace may indicate areas of the coating that have suffered more wear or material removal, while dark areas may represent less affected areas or remnants of the original coating. The higher the hardness and oxide content of the coating, the lower the average wear depth of the coating. FeO had a significant effect on wear resistance due to its hardness and lubricating properties. The results indicate that the No. 2 coating is less worn, which is also confirmed by the results of the wear volume study (Figure 8) and the results of the X-ray diffraction analysis (FeO content increased in sample No. 2). In addition, the reduction of the average wear depth may be favoured by a lower

Sample	Corrosion current I_k ($\mu\text{A}/\text{cm}^2$)	Free corrosion potential E_k (V)	Corrosion rate (mm/year)
Steel 45	3.3807×10^{-5}	0.492	0.3966
1	3.484×10^{-5}	0.43016	0.40872
2	2.1462×10^{-5}	0.46569	0.25178
3	1.0961×10^{-5}	0.43251	0.12859

Table 4. Corrosion parameters of the samples.

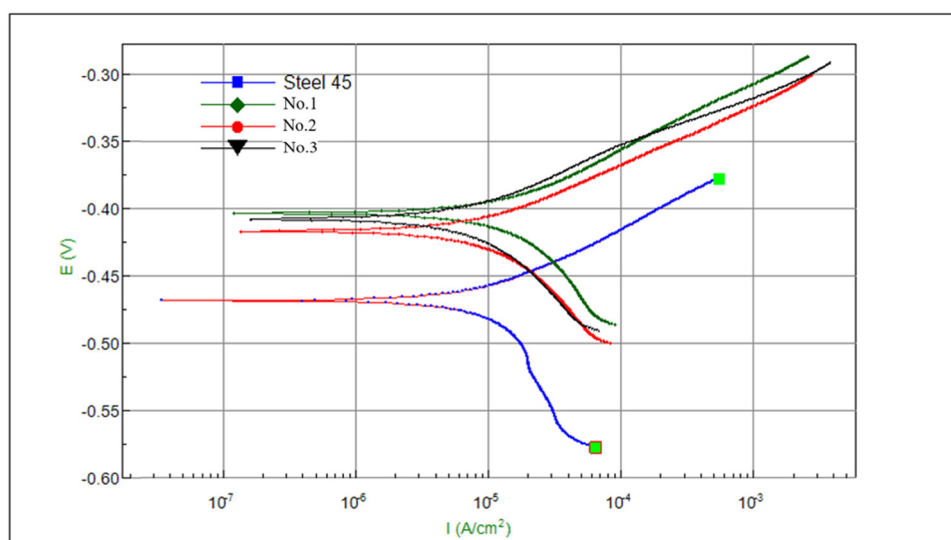


Figure 7. Polarization curves obtained from electrochemical corrosion tests on samples. Tafel extrapolation diagram of electrochemical corrosion measurements at different quenching rates on mild steel samples. E_{corr} : corrosion potential, i_{corr} : corrosion current rate.

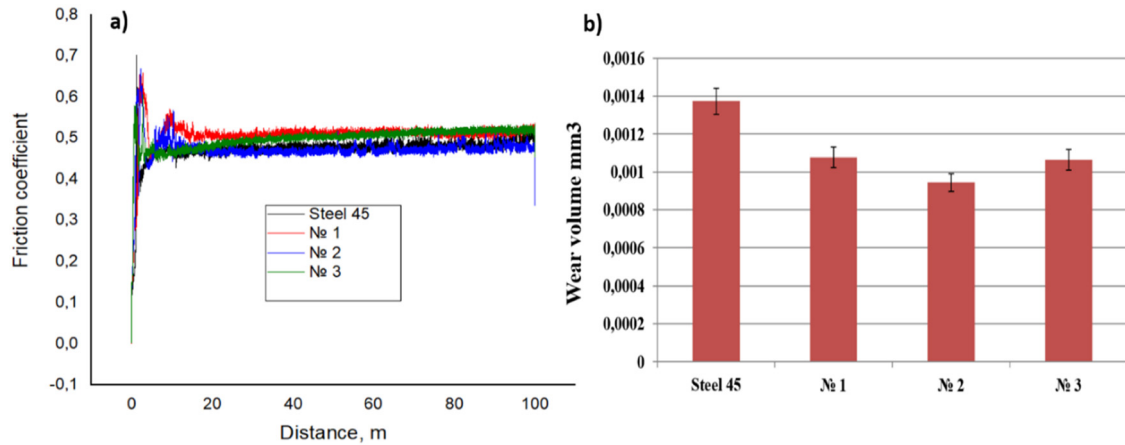


Figure 8. Tribological test results: (a) friction coefficients and (b) wear volume.

friction coefficient due to the formation of oxides in the precipitate.

4. Conclusions

Thus, we have the following conclusions:

- In summary, image analysis showed that changing the parameters of EAM significantly affects the particle size and density of the coatings. Controlling the current and wire feed can be an effective method to achieve optimal characteristics of metallic coatings.
- Investigation of the porosity of the samples confirms that wire feed control affects not only the pore size but

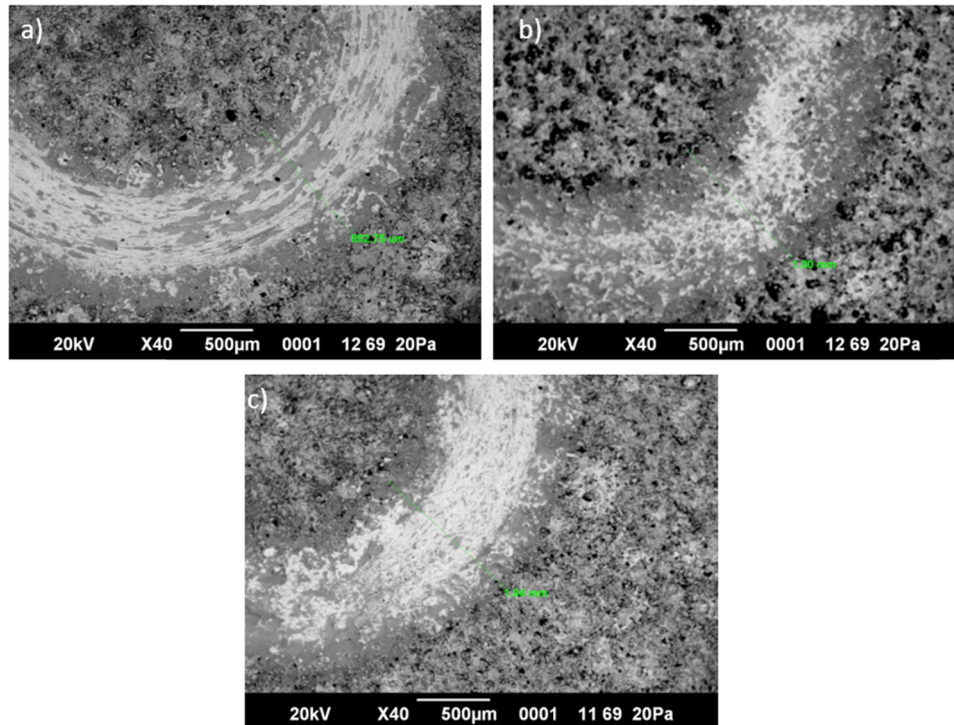


Figure 9. SEM images of a worn surface: (a) No. 1, (b) No. 2, and (c) No. 3.

also the number of pores. Samples with different porosities have different properties due to different process parameters. As a result of the study, the optimal regime of EAM is the parameter processed sample No. 3, where the wire feed rate is 16 cm/s.

- All coatings have a lamellar structure consisting of Fe, iron oxides, and pores. This is a typical microstructure of iron coating produced by super arc sputtering. A large amount of oxides can be observed in coating No. 2 compared to other coatings.
- Minimization of defects such as pores and cracks is critical to improve corrosion resistance. Sample No. 3 with a dense and homogeneous coating structure and smaller pore size shows better corrosion resistance compared to samples with defects in the microstructure.
- The results of the tribological test and wear volume analysis show that FeO also had a significant effect on wear resistance due to its hardness and lubricating properties.

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Author contributions

Bauyrzhan Rakhadilov and Dauir Kakimzhanov formal analysis; supervision; writing–review and editing; Aibek Synarbek and Nazerke Muktanova. investigation; methodology; Rinat Kusainov resources; data curation. All authors have read and agreed to the published version of the manuscript.

Conflicts of interest statement

The authors declare that there is no conflict of interest regarding the publication of this manuscript.

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