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Impact of gas pressure and spray distance on coating formation in electric arc metallization

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This study investigates the technological parameters of electric arc metallization applied to 30KHGSA steel, focusing on the effects of varying the spraying distance (100–250 mm) and gas pressure (6–9 Pa) on the resulting coating structure and properties. The spraying was performed using an SX-600 electric arc metallizer. Electron microscopy and metallographic analysis revealed that the coatings possess a layered structure consisting of solidified convective metal flows, micro-welded particles, and oxide inclusions. The optimal spraying parameters–150 mm distance and 7 Pa pressure–yielded the maximum coating thickness (729.58–733.62 μm) and the lowest porosity (4.02–4.33%). It was observed that increasing the spraying distance beyond 150 mm leads to reduced coating thickness, while deviations from the optimal gas pressure result in decreased structural density and homogeneity. Electric arc metallization of 30KHGSA steel under optimal conditions enables the formation of coatings with enhanced wear resistance and mechanical strength. Specifically, spraying distances over 150 mm and pressures outside the 7–8 Pa range negatively affect the coating's density, uniformity, and tribological performance. The identified optimal range (150–200 mm, 7–8 Pa) promotes the development of coatings with low surface roughness, reduced friction coefficient, and improved wear resistance.

Key words: arc spraying, steel coatings, microstructure, Vickers hardness, porosity, thickness.
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1 Introduction

Arc spraying is a technique that utilizes the heat of an electric arc to melt various metallic materials [1]. Among the coating methods, arc spraying process seems to be more preferred by the criteria of thermal efficiency, cost of atomized materials and ease of maintenance [2,3]. In this method, two consumable wire electrodes are automatically fed into the arc zone. The arc arising between the electrodes melts the wire tips. The principle of arc atomization is based on the atomization of molten metal with compressed air and its deposition on the substrate at high speed, forming a protective coating.

Due to its high productivity and cost-effectiveness, electric arc metallization is widely used in various industries including mechanical engineering, shipbuilding, agricultural and mining machinery. However, the quality of the resulting coatings is highly dependent on spraying parameters such as spray distance and gas pressure. Improper selection of these parameters can lead to defects, increased porosity and deterioration of mechanical properties of the coating. Therefore, optimization of process conditions is an important task to improve the performance of sprayed coatings.

In this paper, coatings of 30KHGSA steel deposited by electric arc metallization on a substrate of 65G steel are investigated. Special attention is paid to the influence of technological parameters of the process – in particular, spraying distance and gas pressure – on the coating formation, its microstructure, thickness, porosity, hardness and surface roughness. Optimization of these parameters will improve the performance properties of coatings and expand their application in agricultural engineering.

Recent progress in electric arc spraying technologies has highlighted the importance of optimizing process parameters to improve coating performance. In particular, steel grade 30KHGSA has emerged as a promising material due to its high mechanical strength, wear resistance, and structural stability under high dynamic loads [1,2]. Its successful application in arc metallization processes is supported by recent works demonstrating its effectiveness in improving surface hardness and adhesion [3]. Thus, selecting 30KHGSA as the coating material is justified by its advantageous performance in demanding industrial environments.

2 Materials and methods

2.1 Equipment and instrumentation

Coating was carried out using supersonic electric arc metallizer SX-600 developed by Guangzhou Sanxin Metal Technology Co (Guangzhou, China). This system consists of power supply, supersonic spray gun, control system and compressed air supply system.

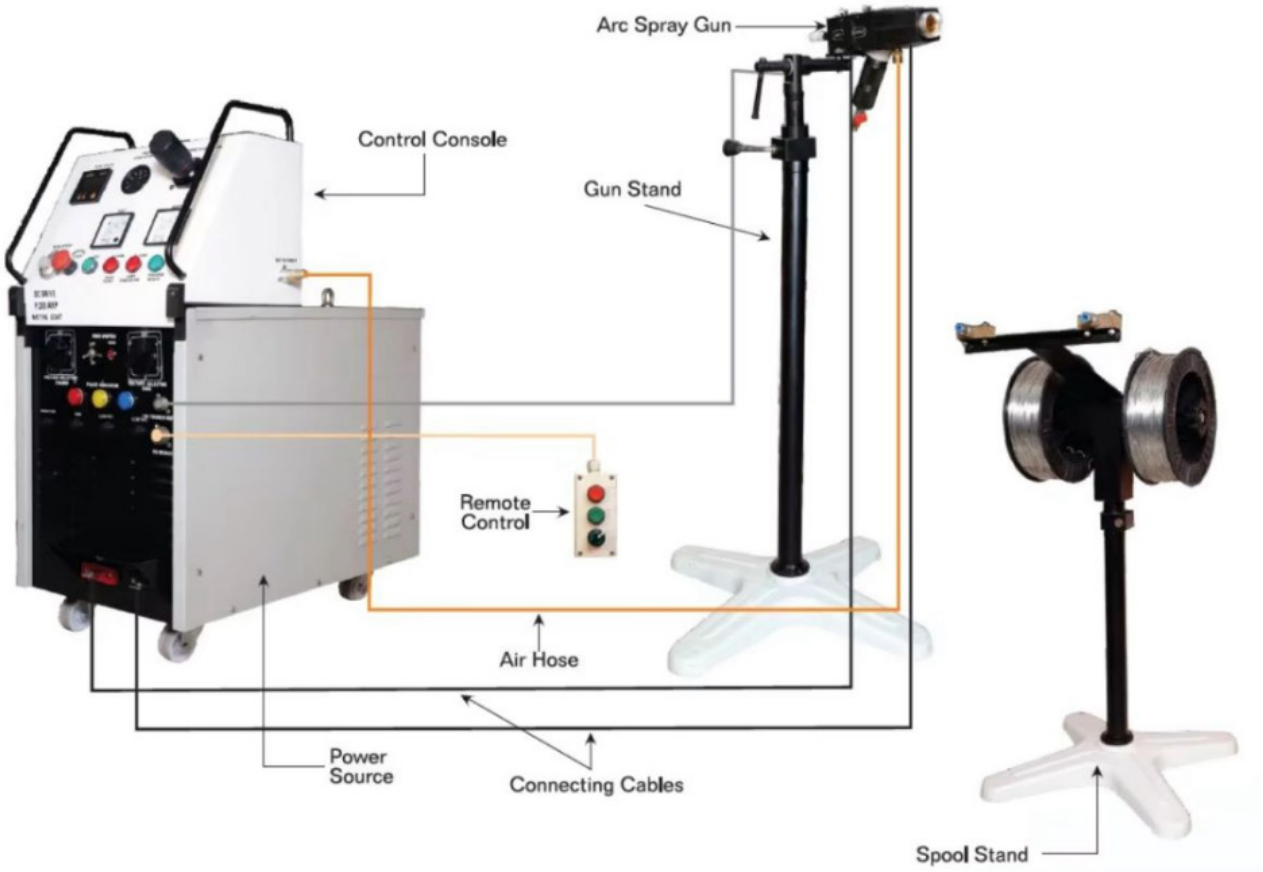


Figure 1 – Schematic diagram of the electric arc metallization setup**.**

The spraying process was conducted according to the modes shown in Table 1, with the parameters varied by varying the gas pressure (P) and spraying distance (D). The substrate temperature was not controlled during the experiment. Future studies will investigate the effect of substrate temperature on coating quality. During the spraying process, the voltage was maintained at the levels shown in Table 1. Air was used as the atomizing gas. Each sample was sprayed for 10 seconds over the entire substrate surface to form a uniform layer. The spraying was carried out under atmospheric conditions. Each experimental condition was repeated 3 times to ensure consistency, with measurements averaged across all trials.

In this work 65G steel (GOST 103-2006) was used as a substrate material. Its ability to harden by hardening significantly increases the service life and wear resistance of parts. Due to these properties, steel 65G is used for the manufacture of springs, springs, washers, friction disks, brake belts, gears, bearing housings, flanges, as well as clamping and feeding collets. This list is not exhaustive, since the universal characteristics of this alloy make it in demand in the production of parts operating under conditions of intensive wear. Steel 65G is widely used in mechanical engineering, machine tool construction, shipbuilding, as well as in the production of heavy military, agricultural and mining equipment. It can be found in almost any mechanism where springs and springs are used. Chemical composition of steel 65G in accordance with GOST 14959-79 is presented in Table 2.

Table 1 – Spraying modes.

Sample	P, Pa	D, mm	I, A	U, B	V, cm/s
D1	9	100	300	45	12
D2	9	150	300	45	12
D3	9	200	300	45	12
D4	9	250	300	45	12
P1	6	200	300	45	12
P2	7	200	300	45	12
P3	8	200	300	45	12
P4	9	200	300	45	12

Table 2 – Chemical composition of steel 65G according to GOST 14959-79.

C	Si	Mn	Ni	S	P	Cr	Cu
0.62 – 0.7	**0.17 – 0.37**	**0.9 – 1.2**	**to 0.25**	**to 0.035**	**to 0.035**	**to 0.25**	**to 0.2**

The coating material used was 30KHGSA steel wire with a diameter of 1.4 mm. This alloy is characterized by high strength, rigidity, as well as good weldability and machinability. Due to these characteristics, 30CrHSA steel is widely used in mechanical engineering and automotive industry. In the automotive industry it is in demand due to its high wear resistance, which makes it an optimal material for the production of crankshafts, connecting rods, cylinder heads and other parts operating under significant loads. In mechanical engineering and construction equipment steel 30CrHSA is used for the manufacture of shafts, axles, gears, bolts and nuts designed for high operating loads. Chemical composition of steel 30KHGSA according to GOST 4543-71 is given in Table 3.

Table 3 – Chemical composition of 30KHGSA steel according to GOST 4543-71.

C	Si	Mn	Ni	S	P	Cr	Cu
0.28 – 0.34	**0.9 – 1.2**	**0.8 – 1.1**	**to 0.3**	**to 0.025**	**to 0.025**	**0.8 – 1.1**	**to 0.3**

2.2 Characterization methods for coatings

To study the structure and porosity of coatings, cross-sections of samples were prepared. Their fabrication was carried out by standard methods of sectioning with subsequent grinding and mechanical polishing. Grinding was carried out using silicon carbide (SiC) based sandpaper with 120 to 3000 grit, and polishing was performed on velvet cloth using 3M polishing paste on a METAPOL 2200P automated grinding machine (Laizhou Lyric Testing Equipment Co., Shandong, China, 2022)[4]. The porosity of the coatings was analyzed using an Olympus BX53M optical microscope (Tokyo, Japan, 2024) [5], at 5× and 10× magnification. Quantification of porosity was performed using Metallographic Analysis Software in accordance with ASTM E2109. The average coating thickness was determined based on five measurements for each image.Roughness measurement was performed by contact profilometry using a 130 profilometer (Proton, Zelenograd, Russia, 2018) [6]. To ensure repeatability of the results and increase the accuracy, five measurements were performed on each sample at random points [7], with subsequent calculation of the parameters Ra (arithmetic mean deviation of the profile) and Rz (the greatest height of the profile) in accordance with GOST 2789-73. Evaluation of surface roughness allowed to determine the influence of different spraying parameters[8].Hardness analysis on the depth of the samples was carried out by the Vickers method using a semi-automatic micro-hardness tester Metolab 502 (St. Petersburg, Russia) in accordance with GOST 2999-75. The optimal combination of these parameters ensures maximum coating durability. Hardness and surface roughness measurements were repeated three times, with measurement errors of ± 5 HV and ± 0.2 μm, respectively. The standard deviations were 2.5 HV and 0.1 μm. Tribological tests were carried out on tribometer TRb3 Anton Paar (international standards ASTM G 133-95 and ASTM G99) under dry friction conditions at room temperature using the standard «ball-disk» method. A 100Cr6 ball of 6 mm diameter was used as the contour[9]. The tests took place at a load of 10 N and a linear velocity of 10 cm/s, the radius of curvature of wear was 3 mm, and the friction path was 400 m.

3 Results and discussions

3 .1 Microstructure

As shown in Figure 2, the microstructure of steel coatings made of 30KHGSA steel by electric arc metallization is a complex heterogeneous system formed as a result of the rapid cooling of molten metal particles during their deposition on the substrate. It consists of individual layer-by-layer deposited splatters (melt droplets of the spraying material), spread and solidified on the substrate [10]. Metallographic analysis of cross-sections reveals a structure characteristic of arc-sprayed coatings, with pronounced layering and heterogeneity [11]. The thickness of individual layers varies widely, and distinct inter-splat boundaries are visible throughout the structure. Spherical and irregular pores are mostly located along the splat boundaries, resulting from gas entrapment and incomplete fusion. Several microcracks, typically oriented perpendicular to the coating surface, can be observed propagating between splats, likely due to thermal shrinkage during rapid solidification. These features – splat boundaries, porosity, and crack networks – confirm the complex interplay between thermal gradients and particle dynamics during deposition, which ultimately affect the mechanical, tribological, and corrosion properties of the coating.

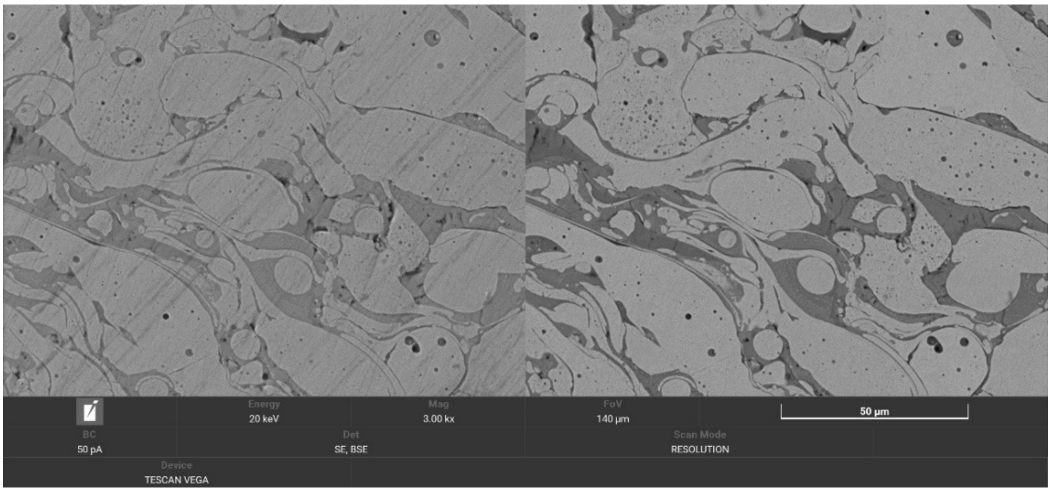


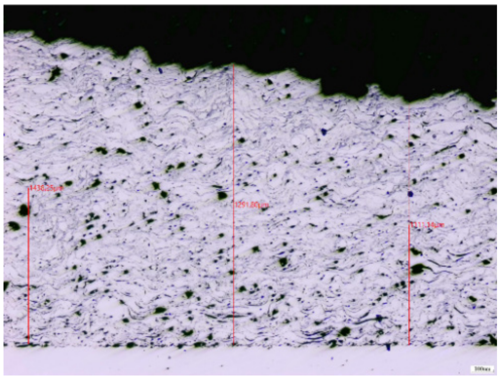
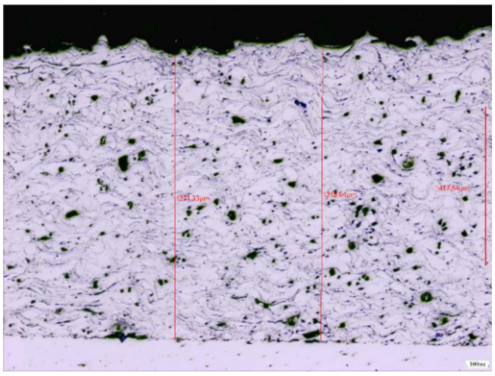
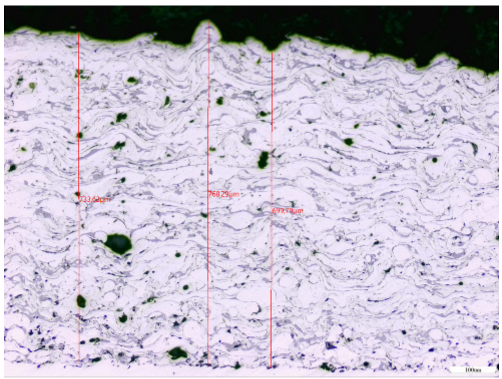
Figure 2 – Layered microstructure of the cross section of the coatings at a magnification of 3.00 kx.

3.2 Thickness and porosity

The coating thickness affects wear resistance and protective properties, while porosity affects density and strength. The relationship between coating thickness and porosity is complex: in a certain range of spraying modes, increasing the distance contributes to a decrease in porosity, but with further increase in distance and gas pressure, there is an increase in porosity due to an increase in the dispersion of particles in the flow[12]. The optimum combination of these parameters ensures maximum durability of the coating.

Table 4 shows the effect of spraying distance (D) on the thickness and porosity of the coating deposited by electric arc metallization. When the distance is increased from 100 to 150 mm, the coating thickness increases from 1291.80 to 1315.04 µm and porosity decreases from 13.92% to 9.80%. However, when the distance is further increased to 200 mm, the thickness decreases sharply to 733.62 µm but the porosity drops to 4.33%. At a distance of 250 mm, the coating thickness becomes minimum (416.27 µm) and porosity increases to 7.21%. This indicates that increasing the distance leads to particle dispersion, reducing the coating thickness. [13]

Table 4 – Dependence of thickness and porosity on distance.

№	Distance dependence of coverage(D)	Coating thickness µm	Photos obtained with metallographic microscope	Porosity of coatings %
D1	100	1291,80		13,92
D2	150	1315,04		9,80
D3	200	733,62		4,33

Continuation of the table

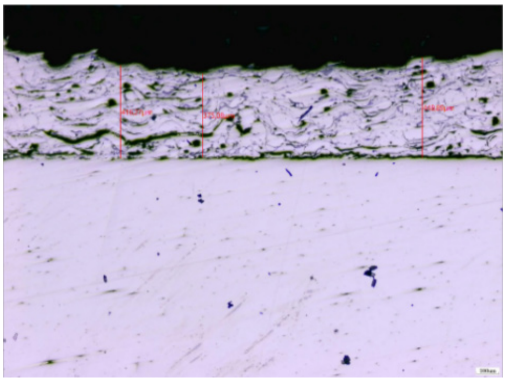
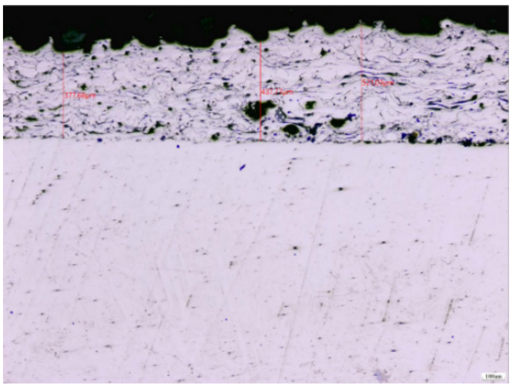
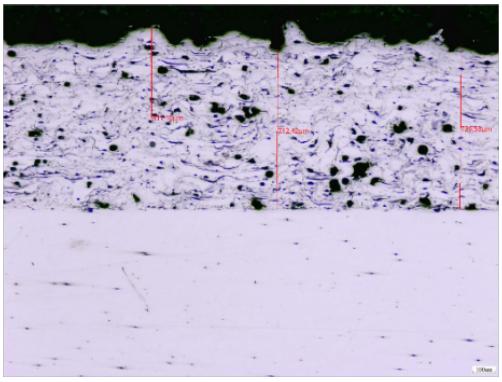
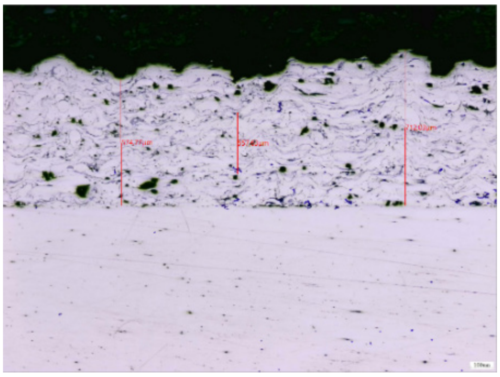
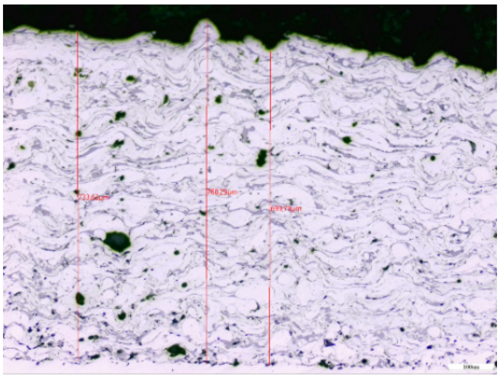
№	Distance dependence of coverage(D)	Coating thickness µm	Photos obtained with metallographic microscope	Porosity of coatings %
D4	250	416,27		7,21

Table 5 shows the effect of gas pressure (P) on the thickness and porosity of the coating deposited by electric arc metallization. At a pressure of 6 Pa, the thickness of the coating is 437.77 µm and the porosity is 9.80%. When the pressure is increased to 7 Pa, the thickness increases to 729.58 µm and the porosity decreases to 4.02%. However, when the pressure is further increased to 8 Pa, the thickness decreases to 557.63 µm and the porosity increases to 5.84%. At 9 Pa, the thickness increases again to 733.62 µm and the porosity remains low (4.33%). These data show that the optimum pressure range is 7-9 Pa, as it achieves the highest coating thickness with low porosity.

Table 5 – Dependence of thickness and porosity on gas pressure.

№	Gas pressire of coverage(D)	Coating thickness µm	Photos obtained with metallographic microscope	Porosity of coatings %
P1	6	437,77		9,80

Continuation of the table

№	Gas pressire of coverage(D)	Coating thickness µm	Photos obtained with metallographic microscope	Porosity of coatings %
P2	7	729,58		4,02
P3	8	557,63		5,84
P4	9	733,62		4,33

Analysis of the data from both tables shows that the thickness and porosity of the coating deposited by electric arc metallization significantly depend on both the spraying distance (D) and the gas pressure (P). The optimum distance interval is 150 – 200 mm. At 150 mm, the maximum coating thickness (1315.04 µm) with moderate porosity (9.80%) is achieved, while at 200 mm, the lowest porosity (4.33%) with the average thickness (733.62 µm) is achieved. Increasing the distance beyond 200 mm leads to a greater reduction in thickness and an increase in coating porosity due to particle dispersion during the spraying process. Regarding the gas pressure, the most favorable range is between 7-9 Pa, since at these values the highest coating thickness (729.58-733.62 µm) with minimum porosity (4.02-4.33%) is achieved. Thus, it is recommended to use a spraying distance of 150-200 mm and gas pressure of 7-9 Pa to obtain an optimal coating.

3.3 Hardness of steel coatings

The hardness of the coating is one of the key parameters determining its wear resistance, durability and mechanical strength. High hardness contributes to the coating's resistance to abrasive wear, shock loads and deformation, which is especially important for parts operating under intensive friction and high loads.

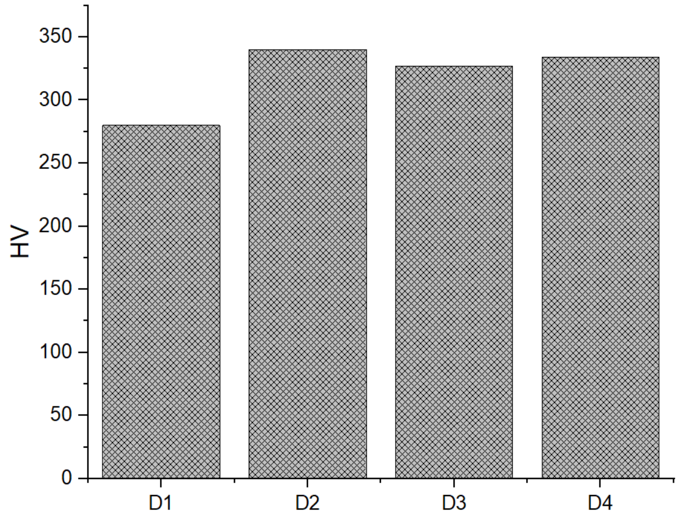


Figure 3 – Variation of coating hardness as a function of varying the distance from the gun to the substrate surface (D is the spraying mode indicated in Table 1).

The graph shows the dependence of the hardness of coatings obtained by electric arc metallization on the spraying distance. The horizontal axis shows different spraying modes (D1-D4). The maximum hardness (340 HV) is achieved in the second mode, whereas in the other cases it decreases to 280 HV.

The data analysis indicates a deterioration in the hardness of the coatings at a spraying distance of 100 mm. A slight increase in the distance improves the hardness, but at a distance of 200-250 mm the values are lower than at 150 mm. Therefore, the optimum spraying distance to achieve the best hardness is 150 mm (Figure 3).

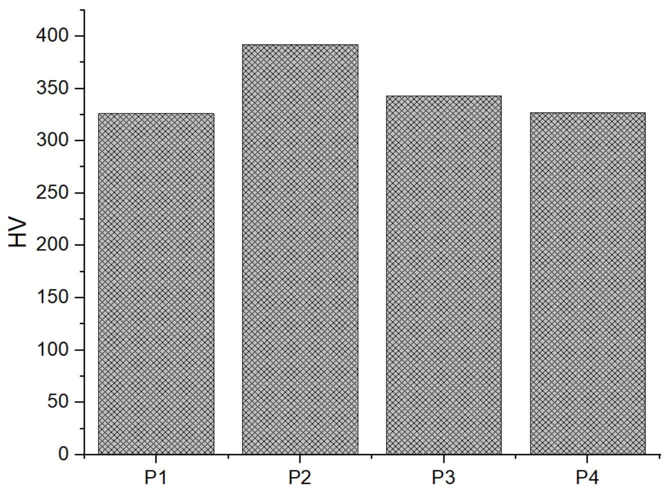


Figure 4 – Variation of coating hardness as a function of varying gas pressure (P is the spraying mode indicated in Table 1).

The graph shows the dependence of the hardness of coatings obtained by electric arc metallization on gas pressure. The horizontal axis shows different spraying modes (1-4).

The maximum hardness (392 HV) is achieved in the second mode at a pressure of 7 Pa, while at other pressure values fluctuations in the range of 326-343 HV are observed. This indicates that both at too low and too high pressures, the coating properties deteriorate, which negatively affects its hardness. Consequently, in this case the optimum pressure is 7 Pa (mode 2).[14,15]

Thus, based on the presented data, we can conclude that both the distance of spraying and gas pressure have a significant effect on the hardness of coatings obtained by electric arc metallization.Therefore, to obtain coatings with maximum hardness, it is necessary to carefully select the spraying parameters, optimizing the distance of 150 mm and gas pressure of 7 Pa.[16](Figure 4).

While the highest hardness observed during the variation of spraying distance alone is achieved at 150 mm (340 HV), the overall maximum hardness of **392.6 HV** is recorded when the spraying distance is **200 mm** and the gas pressure is **7 Pa**. This indicates that the hardness is not solely dependent on a single parameter but results from the **combined optimization** of both spraying distance and gas pressure. Therefore, the best mechanical performance is achieved at 200 mm and 7 Pa, which should be considered the true optimum condition for maximum hardness.

3.4 Roughness

Surface roughness affects the wear resistance, corrosion resistance, adhesion, of materials. The optimum level of roughness is necessary to achieve the best performance characteristics depending on the conditions of use.

Ra (the absolute average deviation relative to the base length) is a parameter that characterizes the average of the deviations of the surface height from its mean value, measured over the entire length of the profile. It is calculated as the arithmetic mean of absolute deviations of the profile height from the mean value. Ra is one of the main roughness indices, where smaller values indicate a smoother surface and larger values indicate a more pronounced roughness.

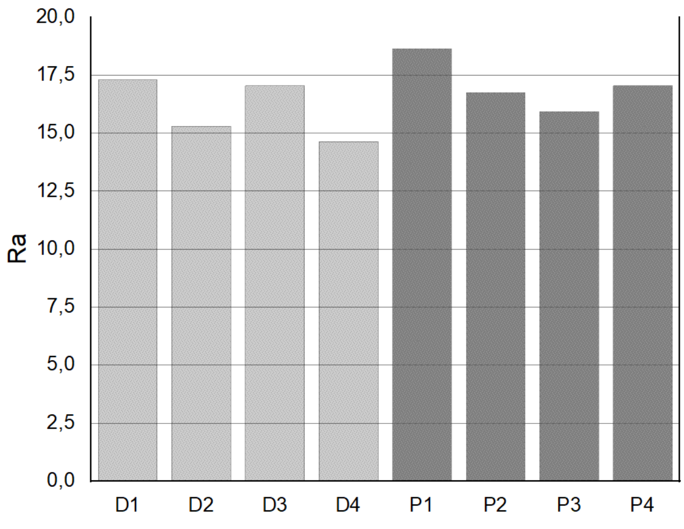


Figure 5 – Variation of coating roughness as a function of varying spraying parameters (D is the distance from the gun to the substrate surface, P is the gas pressure).

As shown in Figure 5, varying the spraying distance affects the surface roughness depending on the selected values. At distances of 100 mm and 200 mm, maximum roughness values of 17.3 µm and 17.04 µm were recorded, respectively. In contrast, the lowest roughness values were observed at spraying distances of 150 mm and 250 mm. At the same time, as the gas pressure (P) increases, the surface roughness initially decreases, reaching a minimum of 15.93 µm; however, further increases in pressure result in a rise in roughness up to 17.04 µm. This behavior may be attributed to the changing dynamics of particle motion in the gas flow. Optimal coating roughness values are achieved through a balanced combination of spraying distance and gas pressure parameters.

Gas pressure plays a critical role in controlling the dynamics of molten particles during arc spraying. As the atomizing gas (typically air) accelerates the molten metal droplets toward the substrate, the pressure determines their velocity, trajectory, degree of fragmentation, and cooling rate. At low pressures (e.g., 6 Pa), particle acceleration is insufficient, which results in lower impact energy, poor flattening, and weak adhesion. This leads to increased porosity and rough surface morphology due to partial fusion and uneven deposition.

When the pressure is increased to an optimal range (7–8 Pa), particles reach a higher velocity and achieve better spreading upon impact, forming flatter splats and denser microstructures with lower porosity. This also improves mechanical properties such as hardness and wear resistance. However, excessive gas pressure (e.g., 9 Pa) may cause high turbulence and particle rebound, leading to inhomogeneous coating, surface defects, and even increased cooling rates that can cause microcracking due to thermal stress.

Therefore, gas pressure must be optimized to ensure a balance between particle speed, splat morphology, cooling behavior, and coating integrity. These effects are consistent with previous studies on high-velocity arc and flame spraying systems [17,18]

3.5 Tribological tests

The spraying distance affects the kinetic energy and degree of oxidation of the coating particles. At the minimum distance (D1, 100 mm), particles are deposited with high energy, forming a dense but potentially overheated coating [19]. Increasing the distance to 150-200 mm (D2, D3) promotes uniform layer formation, reducing the likelihood of defects [20]. At the maximum distance (D4, 250 mm), the particles lose a significant part of energy, which can lead to an increase in porosity and changes in the tribological characteristics of the coating.

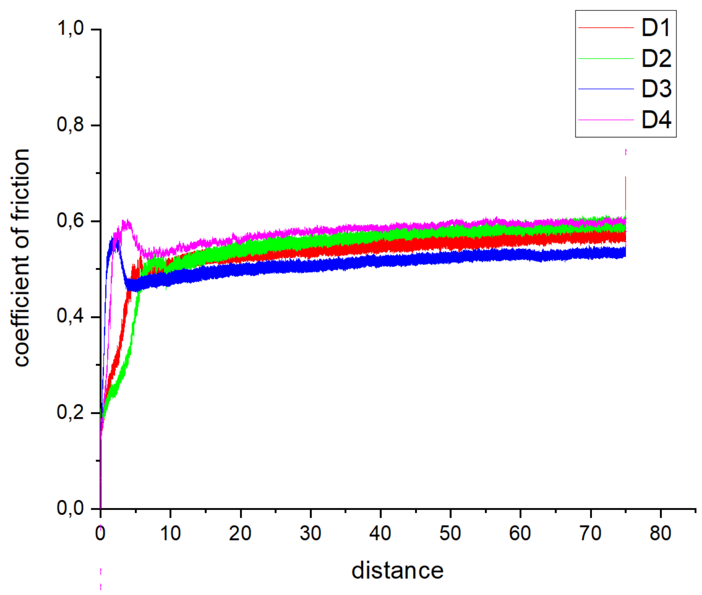


Figure 6 – Dependence of friction coefficient on distance.
(D1-D4 are the spraying mode indicated in Table 1).

Figures 6 and 7 illustrate how spraying distance and gas pressure influence the friction coefficient. As the distance increases, particles acquire different kinetic energies, affecting the wear resistance and tribological properties of the coating. Optimal parameters (distance of 150–200 mm, pressure of 7–8 Pa) result in coatings with a reduced friction coefficient and improved wear resistance. In particular, at a pressure of 7 Pa (P2) and a distance of 150 mm (D2), the most stable and lowest friction coefficient values are observed, correlating with a denser structure and lower surface roughness.

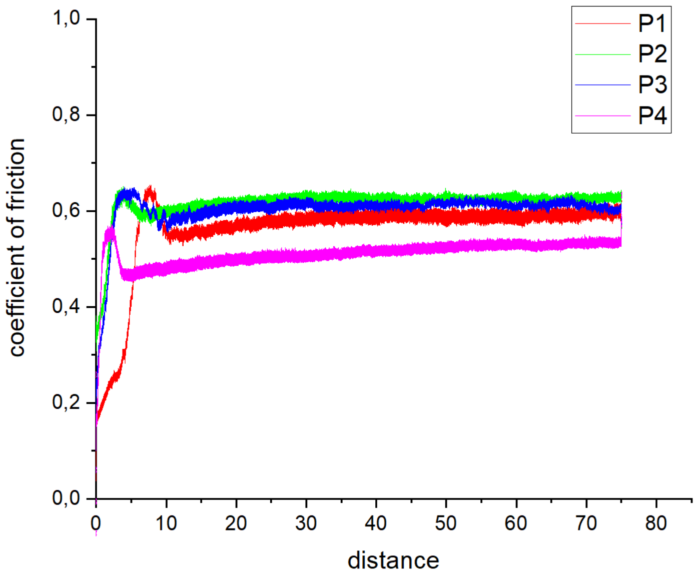


Figure 7 – Dependence of friction coefficient on distance.
(P1-P4 are the spraying mode indicated in Table 1).

Gas pressure determines the atomization rate and the distribution of particles in the flow. At low pressure (P1, 6 Pa) particles have lower kinetic energy, which increases coating roughness and friction coefficient. Increasing pressure (P2-P3, 7-8 Pa) improves the adhesion and density of the coating, making it more homogeneous. At maximum pressure (P4, 9 Pa), excessive particle acceleration is possible, resulting in increased material rebound and inhomogeneity of the coating.

Optimal modes of spraying distance and gas pressure are determined by the balance between the coating density, its adhesion to the substrate and tribological characteristics. Moderate values of distance (150-200 mm) and pressure (7-8 Pa) provide the best combination of friction coefficient and wear resistance of the coating.[21]

4 Conclusion

The conducted study of microstructure and properties of steel 30KHGSA coatings obtained by electric arc metallization has shown that the process of coating formation is accompanied by rapid cooling of molten particles, which leads to the formation of layer-by-layer stacked splats. Optimization of spraying parameters, such as distance and gas pressure, allows achieving the best performance characteristics of the coating, such as maximum thickness (729.58–733.62 μm) and minimum porosity (4.02–4.33%) at a distance of 150 mm and gas pressure of 7–9 Pa. Increasing the spraying distance above 150 mm decreases the coating thickness, and deviation of gas pressure from the optimum values worsens the density and homogeneity of the structure. The influence of spraying distance and gas pressure on the coating hardness is also important: increasing the distance from 100 mm to 150 mm increases the hardness from 280.8 HV to 340.7 HV, and the maximum hardness (392.6 HV) is achieved at a distance of 200 mm and a gas pressure of 7 Pa. The graphical representation showed that the reduction of coating roughness is achieved at certain values of distance, while increasing the gas pressure initially decreases the roughness, but at a certain stage leads to an increase. This behavior can be attributed to the influence of gas pressure on particle velocity and splat formation: at low pressures, insufficient kinetic energy leads to poor adhesion and porosity; optimal pressures enhance particle acceleration, improve splat flattening, and promote rapid solidification; excessive pressure may result in turbulence, rebound effects, and coating inhomogeneity. Thus, parameters such as spraying distance and gas pressure need to be carefully controlled to achieve the required performance properties and increase the mechanical strength of the coating. Analysis of tribological characteristics showed that the distance and gas pressure significantly affect the friction coefficient. Optimal parameters (150–200 mm, 7–8 Pa) provide uniform coating, minimum roughness and high wear resistance.

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