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EFFECT OF WIRE FEED RATE ON THE STRUCTURE AND PROPERTIES OF COATINGS IN THE ELECTRIC ARC SPRAYING PROCESS

ЭЛЕКТРДОҒАЛЫҚ БҮРКУ КЕЗІНДЕ СЫМ БЕРУ ЖЫЛДАМДЫҒЫНЫҢ ЖАБЫН ҚҰРЫЛЫМЫ МЕН ҚАСИЕТТЕРІНЕ ӘСЕРІ

ВЛИЯНИЕ СКОРОСТИ ПОДАЧИ ПРОВОЛОКИ НА СТРУКТУРУ И СВОЙСТВА ПОКРЫТИЙ ПРИ ЭЛЕКТРОДУГОВОМ НАПЫЛЕНИИ

Abstract. *In this work, a study of steel coatings obtained by arc spraying using steel wire of the 30KhGSA grade has been carried out. The main attention is paid to the effect of the wire feed rate on the coating characteristics. The feed rate varied from 2 to 12 cm/sec. The results showed that an increase in the wire feed rate leads to a significant change in the coating characteristics.*

According to experimental data, a direct relationship was found between the wire feed rate and the coating thickness. At a speed of 2 cm/sec, the thickness was 108.4 µm, and at a maximum speed of 12 cm/sec – 733.62 µm. An increase in the feed rate led to a decrease in porosity. The highest porosity (10.45%) was observed at a minimum speed, whereas at a speed of 12 cm/sec, porosity decreased to 4.33%. The analysis of images obtained using a metallographic microscope revealed a layered structure of coatings with alternating light and dark phases. With an increase in the feed rate, the structure was compacted and the number of cracks decreased. X-ray diffraction analysis showed that the largest amount of oxides was formed at the minimum wire feed rate, whereas at the maximum speed oxidation was minimal. Hardness measurements by the Vickers method showed that with an increase in the wire feed rate, the hardness of the coating decreased, although different optimal values were observed for different structures. Optimal roughness values (R_a and R_z) were achieved at a feed rate of 4 cm/sec. Increasing the speed to 8 and 12 cm/sec led to a deterioration in surface roughness.

Keywords: *arc spraying; steel coatings; microstructure; Vickers hardness; porosity; thickness*

Аңдатпа. *Бұл жұмыста 30ХГСА маркалы болат сымы қолданылған электр доғалық металлдау әдісімен алынған болат жабындарын зерттеу жүргізілді. Негізгі назар сымның беру жылдамдығының жабын сипаттамаларына әсеріне аударылды. Сым беру жылдамдығы 2-ден 12 см/сек дейін өзгертілді. Нәтижелер көрсеткендей, сымның беру жылдамдығын арттыру жабын сипаттамаларының айтарлықтай өзгеруіне әкеледі.*

Эксперименттік мәліметтер бойынша сымның берілу жылдамдығы мен жабынның қалыңдығы арасындағы тікелей байланыс анықталды. 2 см/сек жылдамдықта қалыңдығы 108,4 мкм, ал 12 см/сек максималды жылдамдықта 733,62 мкм болды. Жеткізу жылдамдығының жоғарылауы кеуектіліктпоің төмендеуіне әкелді. Ең үлкен кеуектілік (10,45 %) ең төменгі жылдамдықта байқалды, ал 12 см/сек жылдамдықта кеуектілік 4,33 % дейін төмендеді. Металлографиялық микроскоппен алынған кескіндерді талдау ауыспалы жарық пен қараңғы фазалары бар жабындардың қабатты құрылымын анықтады. Жеткізу жылдамдығының жоғарылауымен құрылымның тығыздалуы және жарықтар санының азаюы байқалды. Рентгендік құрылымдық талдау оксидтердің ең көп саны сымның ең аз беру жылдамдығында, ал ең жоғары жылдамдықта тотығу минималды болатынын көрсетті. Викерс әдісімен қаттылықты өлшеу сымның берілу жылдамдығының жоғарылауымен жабынның қаттылығы төмендегенін көрсетті, дегенмен әр түрлі құрылымдар үшін әр түрлі оңтайлы мәндер байқалды. Оңтайлы кедір-бұдыр мәндеріне (Ra және Rz) жеткізу жылдамдығы 4 см/сек болғанда қол жеткізілді. Жылдамдықтың 8 және 12 см/с дейін артуы бетінің кедір-бұдырының нашарлауына әкелді.

Түйін сөздер: *доғалы бүрку; болаттан жасалған жабындар; микроқұрылым; Виккерс қаттылығы; кеуектілік; қалыңдық.*

Аннотация. *В данной работе проведено исследование стальных покрытий, полученных методом электродуговой металлизации с использованием стальной проволоки марки 30ХГСА. Основное внимание уделено влиянию скорости подачи проволоки на характеристики покрытия. Скорость подачи варьировалась от 2 до 12 см/сек. Результаты показали, что увеличение скорости подачи проволоки приводит к значительному изменению характеристик покрытия.*

По экспериментальным данным обнаружена прямая зависимость между скоростью подачи проволоки и толщиной покрытия. При скорости 2 см/сек толщина составляла 108,4 мкм, а при максимальной скорости 12 см/сек – 733,62 мкм. Увеличение скорости подачи привело к снижению пористости. Наибольшая пористость (10,45 %) наблюдалась при минимальной скорости, тогда как при скорости 12 см/сек пористость снизилась до 4,33 %. Анализ изображений, полученных с помощью металлографического микроскопа, выявил слоистую структуру покрытий с чередующимися светлыми и темными фазами. При увеличении скорости подачи наблюдалось уплотнение структуры и уменьшение количества трещин. Рентгеноструктурный анализ показал, что наибольшее количество оксидов образовалось при минимальной скорости подачи проволоки, тогда как при максимальной скорости окисление было минимальным. Измерения твердости методом Виккерса показали, что с увеличением скорости подачи проволоки твердость покрытия снижалась, хотя для разных структур наблюдались различные оптимальные значения. Оптимальные значения шероховатости (Ra и Rz) были достигнуты при скорости подачи 4 см/сек. Увеличение скорости до 8 и 12 см/сек привело к ухудшению шероховатости поверхности.

Ключевые слова: *дуговое напыление; стальные покрытия; микроструктура; твердость по Виккерсу; пористость; толщина.*

Introduction. Thermal spraying technologies include processes where molten or heated materials are sprayed onto the surface of products using electric (plasma, arc (Bobzin, Wietheger, Burbaum, Johann, 2022, Gargasas, Valiulis, Gedzevičius, Mikaliūnas, Nagurnas, Pokhmurska, 2016)) or gas (Rakhadilov, Kenesbekov, Kowalevski, Ocheredko, Sagdoldina, 2020, Zhu, Li, Yang, Ye,2023) installations. These methods make it possible to apply thick coatings (from 20 microns to several millimeters) over large areas at high speed, which makes them effective for industrial applications. Coatings can consist of various materials such as metals, alloys, ceramics and plastics.

The quality of the coatings obtained is assessed on the basis of various characteristics such as porosity, oxide content, hardness, bond strength and surface roughness (Kumar, S, Kumar, R,2021). The general trend shows that an increase in the velocity of the particles used in the spraying process contributes to an improvement in the quality of the coating.

Electric arc spraying (EAS) is a highly efficient metal coating technology widely used in industry and agriculture. This method allows you to restore machine parts, protect metal structures from corrosion, and create coatings from various metals and their alloys.

In the EAS process, the wire melts under the influence of an electric arc and is sprayed with compressed air onto the surface of the product. The use of compressed air or nitrogen provides a stable and high-quality coating.

The key advantages of EAS include high productivity and the ability to apply to various materials. However, with a low wire feed rate, there is a risk of overheating and oxidation, as well as a decrease in the content of alloying elements in the coating (Arif, Shah, Rehman, Tariq,2020). It is important to take these limitations into account so as not to degrade the mechanical properties of the parts being restored.

Materials and methods of research. Coating spraying was performed using a supersonic electric arc metallizer SX-600, manufactured by Guangzhou Sanxin Metal Technology Co (Guangzhou, China) (Rakhadilov, Shynarbek, Kakimzhanov, Kusainov, Zhassulan, Ormanbekov,2024). This complex includes a power supply, a supersonic spray gun, a control system and a compressed air system.

The spraying of the wires was carried out in accordance with the modes indicated in Table 1. The parameters in these modes varied by changing the wire feed rate (V). The voltage during spraying was maintained at the level shown in Table 1, their characteristics increase as the wire feed rate increases. Air was used as the spraying gas. Each sample was sprayed over the entire surface of the substrate for 10 seconds to obtain a uniform layer.

Table 1. Spraying modes

Sample	P, Pa	D, mm	I, A	U, B	V, cm/s
№ 1	9	200	200	30	2
№ 2	9	200	200	40	4
№ 3	9	200	300	40	8
№ 4	9	200	300	45	12
Note – compiled by the authors					

In this work, grade 65G steel (GOST 103-2006) was used as the substrate material. 65G steel is widely used in mechanical engineering, machine tool construction, shipbuilding, as well as in the production of heavy military, agricultural and mining equipment. Springs, washers, friction discs, brake belts, gears, bearing housings, flanges are made of 65G steel. The possibility of improving the properties of 65G steel by quenching significantly extends the service life and increases the wear resistance of parts. The composition of 65G steel according to GOST 14959-79 is shown in Table 2.

Table 2. The content of elements in 65G steel 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	up to 0.25	up to 0.035	up to 0.035	up to 0.25	up to 0.2
Note – compiled by the authors							

Steel wire of the 30KhGSA grade, with a diameter of 1,4 mm, was used as the coating material. 30KhGSA steel is characterized by high strength and rigidity, as well as excellent weldability and machinability properties. Due to these qualities, it is widely used in mechanical engineering and the automotive industry. 30KhGSA steel is used in the manufacture of crankshafts, connecting rods, cylinder heads and other parts. In mechanical engineering and in the manufacture of construction equipment, this steel is used to produce shafts, axles, gears, bolts and screws designed for significant loads. According to GOST 4543-71, 30KhGSA steel has the following composition (Table 3).

Table 3. The content of elements in 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	up to 0.3	up to 0.025	up to 0.025	0.8 - 1.1	up to 0.3
Note – compiled by the authors							

Cross sections of the samples were prepared to study the structure and porosity of the coatings. The samples were made using standard partitioning methods followed by grinding and mechanical polishing. Grinding was carried out using sandpaper with a grain size from 120 to 3000 based on silicon carbide (SiC), and polishing was carried out on velvet fabric using 3M polishing paste on an automatic grinding machine of the METAPOL 2200P model (Laizhou Lyric Testing Equipment Co, Shandong, China). To study the porosity of coatings using an optical microscope (Olympus BX53M, Tokyo, Japan), images were taken with magnification of 5X and 50X. Porosity was calculated using Metallographic Analysis Software in accordance with the ASTM E2109 standard. The average coating thickness was determined based on five measurements for each image. The roughness of the coatings was measured by contact profilometry using a profilometer 130 (Proton, Zelenograd, Russia, 2018) (Rysin, 2017). To ensure the repeatability of the results and minimize the error, five measurements were carried out on each sample in random places, followed by the calculation of the values of Ra (arithmetic mean deviation of the profile) and Rz (maximum profile height) according to GOST 2789-73. The analysis of the surface roughness values was carried out to assess the effect of various spraying parameters. According to the Vickers method, a semi-automatic micro hardness tester (Metolab 502, St. Petersburg, Russia) was used in accordance with GOST 2999-75. X-ray diffractometer X'pertpro (Philips Corporation, Eindhoven, the Netherlands) was used to determine the phase composition.

Results and discussion. Based on the images obtained using a metallographic microscope, it was found that when spraying by arc spraying, layered coatings with a certain porosity are formed. (Khan, 2019).

The analysis showed that the structure consists of light and dark areas (Figure 1), and they change with each other. Alternating lamellae of both phases are observed in all samples. Rounded light phases inside dark areas were also revealed. The dark areas have cracks, while the light areas do not and seem to prevent cracks from spreading from the dark areas (Rakhadilov, Magazov, Kakimzhanov, Apsezhanova, Molbossynov, Kengesbekov, 2024).

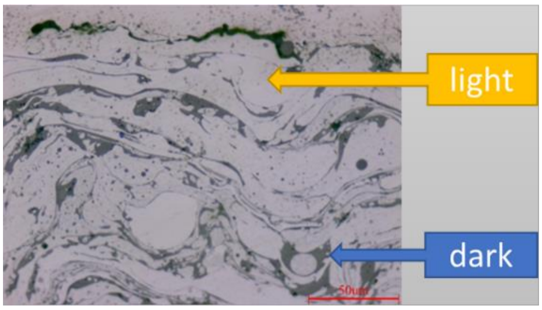


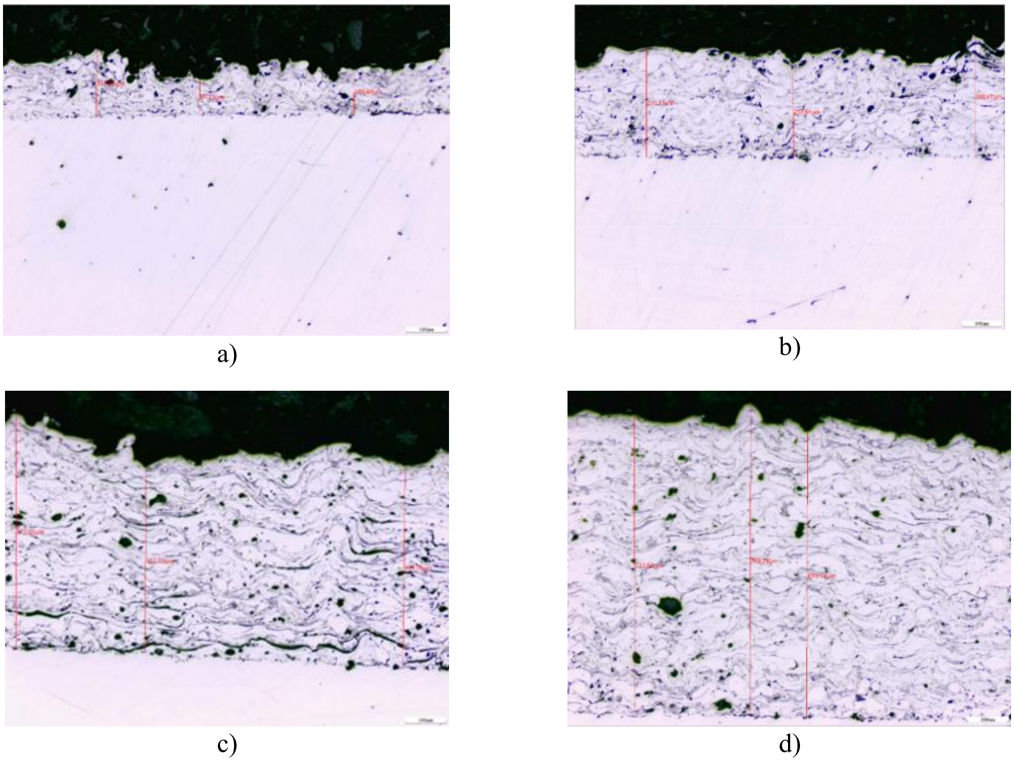
Figure 1. An image of a metallographic microscope with a magnification of 5X
Note – compiled by the authors

Thickness and porosity are the key properties that determine the characteristics of coatings. In Table 4, you can see how these properties change depending on the deposition rate.

Table 4. Results of coating thickness and porosity

№	Wire feed rate, cm/sec	Coating thickness, *μm*	Porosity of coatings, %
1	2	108,4	10,45
2	4	276,9	12,59
3	8	491,78	8,38
4	12	733,62	4,33
Note – compiled by the authors			

The effect of the wire feed rate on the coating thickness shows a direct relationship: with increasing speed, the coating thickness increases. Figure 2 shows the images obtained using a metallographic microscope. The porosity of the coatings also decreased with an increase in the wire feed rate, reaching minimum values of 8.38% and 4.33% at 8 and 12 cm/s, respectively. An increase in the wire feed rate leads to an increase in the volume of the sprayed material, which contributes to a greater formation of the coating thickness. This can also lead to a denser coating by better filling the surface and reducing the number of pores and voids. Additionally, an increase in the wire feed rate leads to more particles settling on the surface, which enhances. The impact on the already applied layers helps to seal the coating, reducing its porosity.



a) b) c) d)

Figure 2. Image of coating thickness obtained with a metallographic microscope:
a) Sample № 1; b) Sample № 2; c) Sample № 3; d) Sample № 4

Note – compiled by the authors

Figure 3 shows the results of X-ray diffraction analysis (XRD) for four samples designated as № 1, № 2, № 3 and № 4. The graphs show the intensity of scattered X-ray radiation depending on the diffraction angle.

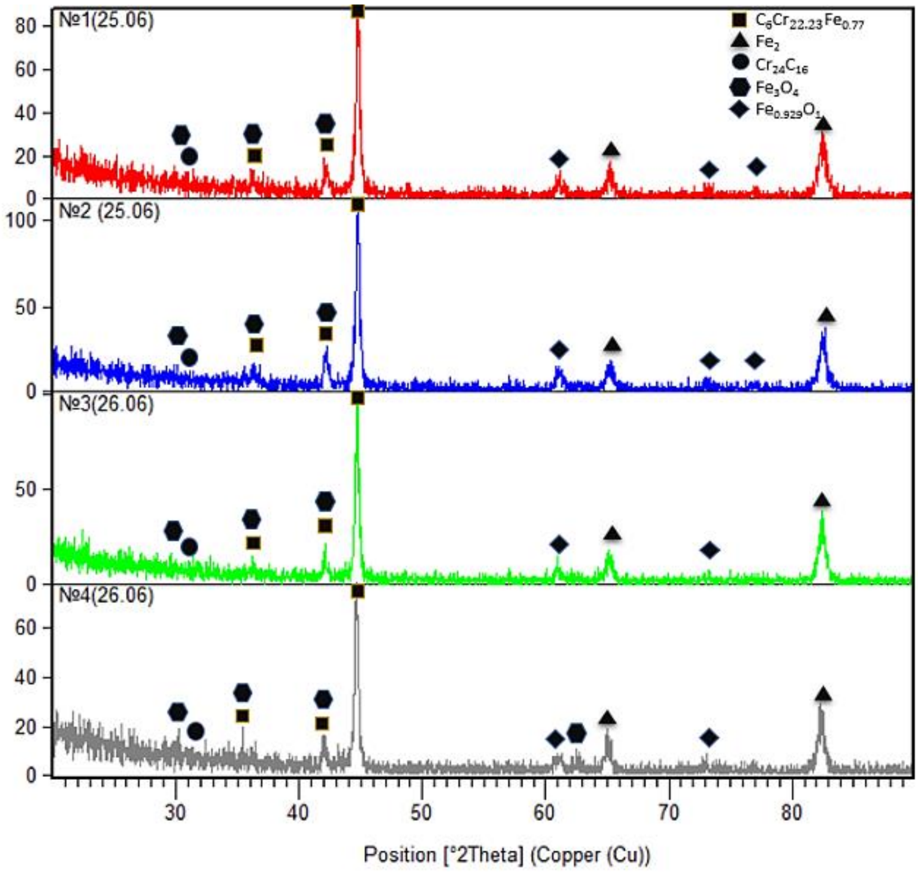


Figure 3. X-ray of steel coatings

Note – compiled by the authors

The results of X-ray phase analysis revealed oxides, which are shown in Figure 3. The proportion of oxides (Fe_3O_4, Fe0.929O1) on samples No. 1, No. 2 and No. 3 was slightly higher at low wire feed. The lowest oxide intensity was observed on sample No. 4, where it was significantly lower, and the wire feed was the highest among all samples. The presence of these phases, shown in Figure 3, indicates the presence of oxidation processes on the surface of the samples. This can be explained by the fact that spraying occurs in the atmosphere.

The results of hardness measurements on the Metolab-502 microhardness tester are shown in Figure 4.

Figure 4 shows the data on the hardness of the material when the wire feed rate changes. Hardness was shot in two different areas (light and dark) as shown in Figure 4. The dark area mainly consists of oxides (Fe_3O_4,Fe0.929O1). The light layer mainly consists of phases. With an increase in the wire feed rate from 2 cm/sec to 12 cm/sec, there is a general tendency to decrease the hardness of the material, except for some differences.

For a coating with a "gray" structure, the maximum hardness is observed at a wire feed rate of 8 cm/sec, which differs from a coating with a "white" structure, where maximum hardness is achieved at a minimum feed rate.

The optimal feed rate may vary depending on the type of structure, although the material is the same. For the "gray" structure, the optimal hardness is achieved at an average feed rate (8 cm/sec), whereas for the "white" structure – at a minimum speed (2 cm/sec).

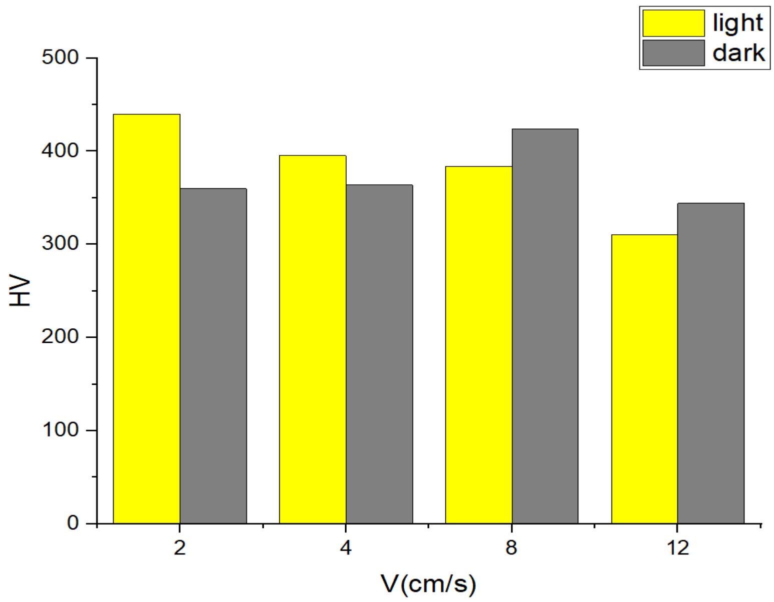


Figure 4. The hardness of steel coatings in two different structures
Note – compiled by the authors

According to the presented data, it can be concluded that white and gray structures are inversely dependent on each other in the process of changing the deposition parameters. White structures show improved performance when the wire feed rate decreases, whereas gray structures, on the contrary, improve when the feed rate increases. This inverse proportionality indicates their interdependence, where optimization of one parameter contributes to the development of certain phases and structures that affect the mechanical properties of the coating. (Wagner, 2021, Logachev, Litovchenko, 2014).

Surface roughness plays an important role in determining the performance properties of the coating, such as wear resistance and corrosion resistance. To quantify the surface roughness, the parameters R_a (the arithmetic mean deviation of the profile) and R_z (the height of the profile irregularities at ten points) were selected in Figure 5. The change in the parameters of the surface roughness of the steel coating at different wire feed speeds (V, cm/s) is shown.

The analysis shows that at a low wire feed rate of 2 cm/s, relatively high values of both the parameter R_a (17,04 μm) and R_z (81,23 μm) are observed, which may indicate a rougher surface texture with a large number of irregularities. An increase in the feed rate to 4 cm/s leads to a significant decrease in both parameters, which indicates a smoother surface. With a further increase in velocity to 8 cm/s, the parameters R_a and R_z increase to values 13,96 μm and 81,28 μm, respectively, which indicates a deterioration in surface roughness and an increase in the number of irregularities. At a maximum feed rate of 12 cm/s, the R_a and R_z values remain high, confirming the rough texture of the coating (Johnston, Hall, McCloskey, 2013).

The optimal roughness of the coating is achieved at a wire feed rate of 4 cm/s, at which the roughness values are minimal. An increase in speed leads to an increase in roughness, which negatively affects the surface quality (Kang, 2017).

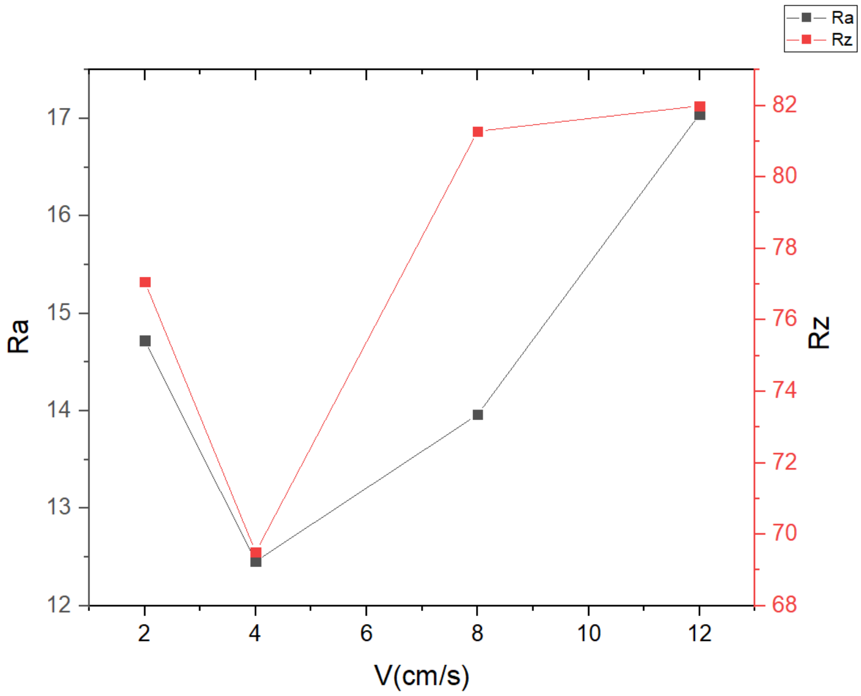


Figure 5. Roughness parameters R_a and R_z.

Note – compiled by the authors

Conclusions. As a result of the conducted research, it was found that the parameters of arc spraying, in particular the wire feed rate, have a significant effect on the characteristics of the coatings obtained. According to the results of the X-ray phase analysis with the entrainment of the wire feed rate, two different layers are visible with different whistles and this affects the hardness of the coatings. The microstructures show that the layer consists of light and dark areas. An increase in the wire feed rate leads to an increase in the thickness of the coating and a decrease in its porosity, which improves the overall microstructure of the coating. At the same time, an increase in the feed rate is accompanied by a decrease in the hardness of the coating and an increase in surface roughness, which indicates the need for precise selection of the spraying mode depending on the required performance characteristics of the coating. Thus, the optimization of the deposition parameters makes it possible to achieve a balance between mechanical and structural characteristics, which opens up prospects for the widespread use of arc spraying in industry.

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Notice of the use of generative AI and AI-enabled technologies in the writing of the manuscrip. The author group did not use generative AI in the preparation of this article.

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