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Formation of Wear-Resistant Coatings by Surfacing in a Shielding Gas Environment

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Abstract. This paper investigates the wear mechanisms of rotary mining cutters operating under abrasive and impact loading conditions and presents science-based approaches to improving their service life. During the study, gas metal arc welding (GMAW) hard-facing technology was applied to produce wear-resistant coatings using flux-cored wires EnDOtec DO351, EnDOtec DO332, and EnDOtec DO*11. Structural carbon steel C45, widely used in mechanical engineering, was selected as the base material. Hard-facing of experimental samples and cutting edges of rotary cutters were carried out using a CNC-controlled robotic three-axis system developed at AGH University of Science and Technology (Krakow, Poland). A comprehensive analyses, including metallographic, mechanical, and hardness were performed to determine the structural features and strength characteristics of the obtained coatings. In addition, the elemental composition of the deposited layers was analyzed using energy-dispersive spectroscopy (EDS). Microstructural analysis revealed the formation of chromium-rich carbide phases, which ensure high resistance of the coating to abrasive wear. Microhardness measurements showed that the hardness of the hard-faced layer significantly exceeds that of the base metal, reaching a maximum value of 1705 HV. The obtained results confirm the high efficiency of hard-facing technology in improving the wear resistance of rotary mining cutters and enhancing the reliability of mining machine working elements. The scientific novelty of this work lies in the comprehensive evaluation of the structural features of coatings obtained using GMAW technology and their influence on wear resistance.

Keywords: rotary mining cutter, hard-facing, wear resistance, hardness, flux-cored wire, GMAW, mechanical properties

Introduction

In the modern engineering industry, increasing the service life of machinery and equipment, especially in mining, is considered as one of the most important engineering tasks. Drilling tools and tangentially rotating ore cutting blades, operating in the conditions of an abrasive environment are subject to significant wear effects. As a result of gradual damage to the working surface, their original geometric shape changes, material consumption occurs, leading to premature failure of equipment. Such changes negatively affect the stability of the production process, increasing the cost of maintenance and replacement of parts.

The phenomenon of wear is considered a complex and multifactorial physico-mechanical process. Under abrasive action, solid mineral particles penetrate the metal surface, causing destruction of the material structure by micro-cutting and micro-bending mechanisms. In addition, as a result of dynamic impact loads, cracks are formed at the microstructure level, and their gradual increase reduces the strength of the material. In this regard, the problem of strengthening the surface and increasing the wear resistance of working bodies is of particular scientific and practical importance [1].

As one of the most effective wear-preventing solutions, melt plating technology is widely used. This method allows to form an alloy layer on the surface of the base material, with properties determined in advance, characterized by its high hardness and wear resistance. Such coatings take on the abrasive and shock effects that arise during operation and significantly slow down the destruction of the base metal. As a result, the service life of the part is extended and its reliability increases.

Gas Metal Arc Welding (GMAW) technology, implemented in a protective gas environment, is one of the most widely used methods in the smelting coating process. The main advantage of this technology is the ability to accurately adjust the parameters of heat input, due to which, the depth and structure of the melting zone are controlled. In addition, the GMAW process creates conditions for uniform and high-quality coating of surfaces of complex shapes, if combined with automated or robotic systems. This, in turn, ensures the stability of the technological process and increases the repeatability of the properties of the resulting coating.

The main goal of the research work is to increase the wear resistance of Rotary mining knives by the method of melting coating and a comprehensive assessment of the structural – phase State, as well as mechanical characteristics of the resulting coatings. To achieve this goal, in the course of experimental studies, the microstructure of the coating layers, hardness indicators and features of their distribution by thickness were determined.

The experimental part of the work consisted of several interrelated stages. At first, the base metal surface was subjected to mechanical processing and cleaned of impurities and oxide layers. After that, the melting coating process was carried out in the selected modes: parameters such as welding current, voltage, wire feed speed and protective gas consumption were optimized. In the process of coating, a layer of material was applied in layers and formed to the required thickness.

After the completion of the coating, the samples obtained were prepared for metallographic analysis: they were cut, sanded and polished. Microstructural studies were carried out using optical and electron microscopy methods, as a result of which phase changes and structural features in the composition of the coating were revealed. In addition, the distribution of mechanical properties in different areas of the coating layer was studied by measuring micro-strength. These measurements made it possible to assess the strength properties of the coating and determine the main indicators characterizing its wear resistance.

Assessment of the effectiveness of the implementation in production and the possibilities of application of the proposed technology in terms of increasing the operational resource of cutting tools and reducing operating costs in specific operating conditions of mining production.

In recent years, the international scientific community has paid special attention to the study of the microstructure and phase composition of connective coatings. In 2023 studies, Badisch and colleagues showed that the wear resistance of Chromium-based coatings directly depends on the morphology and distribution features of carbide Phases [3]. In 2024, García-León et al systematically studied the influence of welding parameters on microstructure formation and found that there is a correlation relationship between heat input energy and Carbide size. Chromium-rich powder wires contribute to the formation of abrasive wear-resistant carbide phases (Cr_7C_3, $Cr_{23}C_6$) [4]. Therefore, it is relevant to conduct research on melt coating technology.

For the machine-building industry of Kazakhstan, especially in the context of mining enterprises, increasing the wear resistance of equipment is considered one of the most urgent tasks from an economic point of view. Taking into account the peculiarities of local production, a scientifically based approach is required for the correct selection of effective packaging materials and melting coating parameters [5].

1. Materials and methods

Rotary is the identification and scientific justification of effective technological approaches aimed at increasing the wear resistance of mining knives. The object of the study was considered the laws of the influence of the technological parameters of the melting coating process and the chemical composition of wear-resistant coatings on the structural-phase State of the working surface of the Blades, the features of the microstructure, the level of micro-strength and tribological characteristics.

In the process of preparing experimental samples, structural carbon steel of grade 45, common in the mechanical engineering industry, was used as the main material (Figure 1).

Fig. 1. - The rotating performing body for rock destruction and the wear-resistant coating on the conical geometry mining knife: a) the general view of the rotating performing Body; B) the mining knife with a melt-coated coating.

The study considered Steel C45 (DIN 1.0503/ISO 683-1 1987) as the main material. This material is medium carbon structural steel and is widely used in Mechanical Engineering [6]. Table 1 presents the chemical composition of C45 steel recommended by the manufacturer.

Table 1. Chemical composition of C45 steel

Element	C	Si	Mn	P	S	Cr	Ni	Mo	Cu
Mass. %	0,42-0,50	0,15-0,35	0,50-0,80	<0,035	<0,035	<0,30	<0,30	<0,10	<0,30

The carbon equivalent (CE) lies between 0.52-0.82, depending on the calculation standard, which indicates the difficulty of welding the material.

The study looked at three different metal core powder wires from Castolin Eutectic: EnDOtec DO*351* (wire A), DO*332* (wire B) and DO*11 (wire C). All wires are designed for chrome-rich and abrasive working environments [6]. Table 2 presents the chemical composition of the wires.

Table 2. Chemical composition of powder wires

Wire	C(%)	Cr (%)	Si(%)	Mn(%)	Mo(%)	Ni(%)	Fe(%)
DO*351	4,5-5,2	26-30	0,8-1,2	0,5-1,0	0,5-1,5	<2,5	Waste
DO*332	3,8-4,5	22-26	1,0-1,8	0,8-1,5	1,0-2,0	<3,0	Waste
DO*11	5,0-5,8	28-32	0,5-1,0	<1,0	<1,0	<2,0	Waste

The diameter of all wires is 1.6 mm. Due to the metal core structure, the actual cross-section is slightly smaller and may vary in coil length [6].

The smelting coating process was carried out on robotic three-axis equipment with digital software control, located at EVH and the University of Science and technology (Poland). The unit is equipped with an additional fourth axis of rotation, which makes it possible to process complex spatial surfaces. The working area is 320 × 300 × 170 mm, and the moving speed of the melting coating head is adjustable in the range of 0.1–200 mm/s. A voltage of 22 V, A Current of 160-453 a, a coating speed of 400 mm/min and a wire feed speed of 3-10 m/min were used as technological parameters. A mixture of 82% argon and 18% carbon dioxide was used as a protective gas, and its consumption was kept at the level of 15 l/min [6].

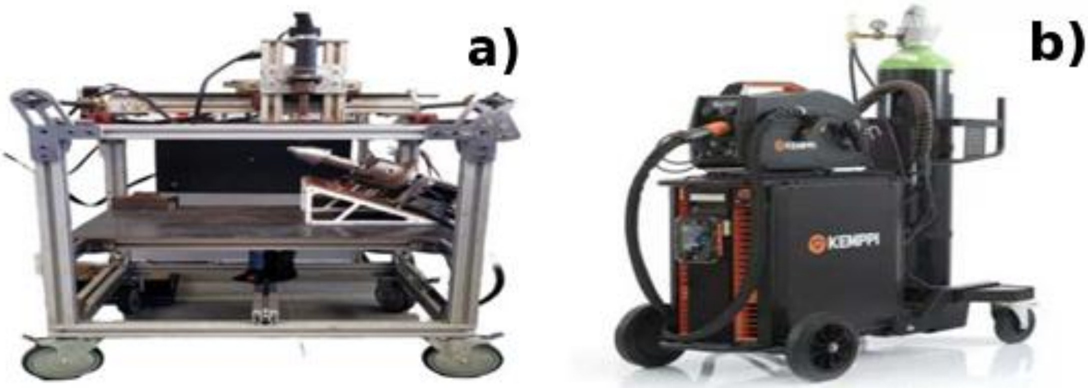


Fig. 2. - Equipment used in the smelting plating process: a) 4-axis test station for melting coating of welding joints (melting coating process); b) current source used in the research

The main technical means used in the study are presented in Figure 2. To carry out the experimental work, a four-axis test station for melting coating of welding seams was used, with the help of which all stages of the coating process were carried out in an automated mode. In addition, the Kemppi X8 semi-automatic complex was used as a source of welding current, according to which a wire feeder was introduced. This equipment is adapted for stable operation at high current values and can bring the current value up to 600 A under short-term load.

Such technical characteristics allow you to accurately control the melting coating process, including adjusting the heat input parameters. As a result, the structure of the formed coating layer becomes uniform, and conditions are created for a targeted change in its mechanical properties.

The technology of smelt plating by the GMAW method is distinguished by its versatility and wide application in production conditions. Among the main advantages of this approach are its technological simplicity, flexibility of application and relatively affordable cost of equipment.

There are two main types of the mentioned technology: MIG and MAG. The MIG (Metal Inert Gas) process is based on the protection of the welding area with inert gas, and in the MAG (Metal Active Gas) method, chemically active components are added to the protective gas composition. Inert gases usually include argon and helium or their mixtures, and carbon dioxide, oxygen, nitrogen, and hydrogen are used as active gases. In addition, various combinations of these gases are also widely used in the experiment, including formulations mixed together with argon or helium [7-8].

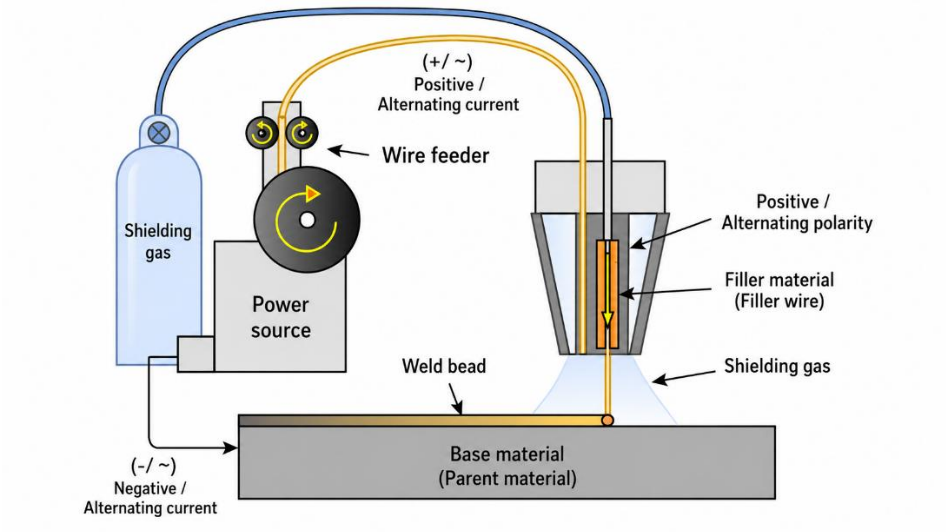


Fig. 3. - Diagram of the arc melting coating process using a melting electrode in a protective gas environment

In the course of this study, the GMAW method performed in a protective gas environment was used to implement the melting coating process, which made it possible to ensure the high quality, structural uniformity and wear resistance of the coating layer.

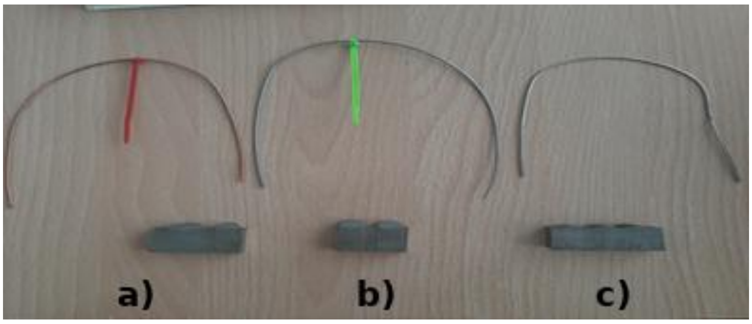


Fig. 4. - Experimental samples manufactured on the basis of EnDOtec DO351 (a), DO332 (b) and DO*11 (c) powder wires

Preparation of samples for macrostructural and hardness studies was carried out in the testing laboratory of the engineering profile "VERITAS" at D. Serikbayev ektu. As shown in Figure 4, the study examined three different brands of metal core powder wires.

The preparation of macroschliffs was carried out according to the standard metallographic methodology: coarse grinding, fine grinding, diamond polishing with slurry (9-1 microns) and treatment with 10% nitric acid.

Fig. 5. - Equipment for metallographic research: a) sample preparation device; b) optical microscope

In the work, the elemental composition of the coated layers was determined by the method of energodispersion analysis, and the micro-density was measured by the Vickers method. These studies make it possible to comprehensively assess the structural features and mechanical properties of melt-coated coatings. Metallographic studies were carried out under the Olympus BX51 microscope (Japan) with a computing station equipped with the Mineral C7 program. In addition, the method of X – ray energodispersion microanalysis (EDX-Energy Dispersive X-Ray microanalysis) was used (Figure 5).

2. Results and discussion

The metallographic and energy-intensive studies made it possible to determine the structural features and elemental composition of the molten coating layer.

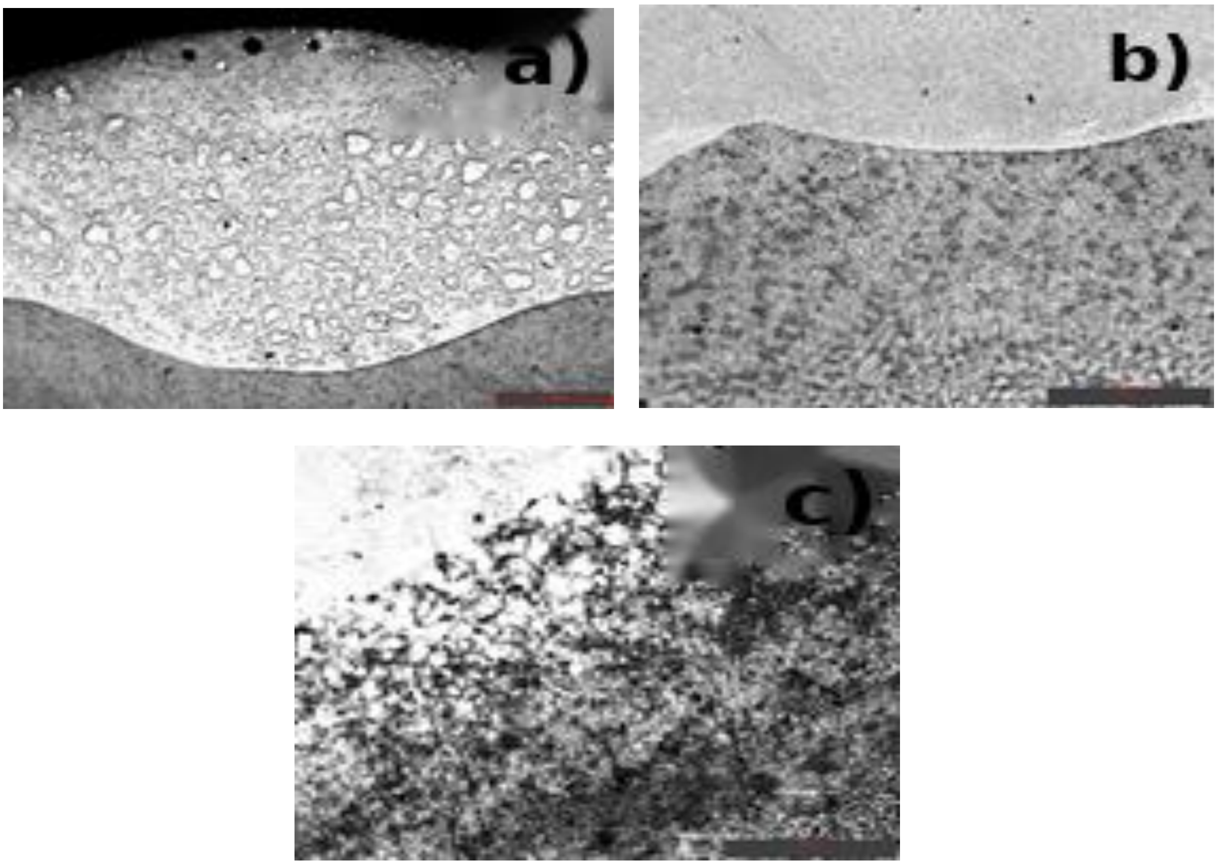
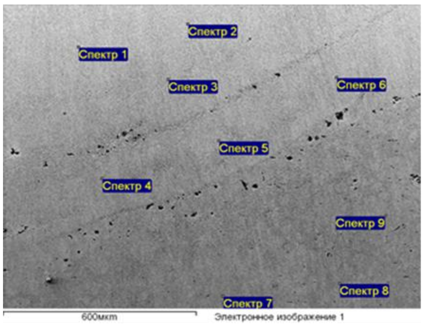


Fig. 6. - Microstructure of the molten coated layer: a) general structure of the coated layer; b) microstructure of the transition zone; c) distribution of carbide phases

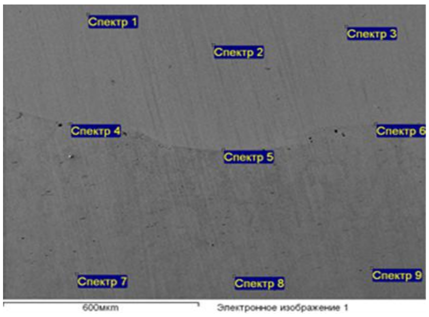
The results of microstructural analysis showed that a heterogeneous structure was formed in the melt-coated layer, characterized by a uniform distribution of structural components. This structure is distinguished by a harmonious combination of Matrix and solid phases and provides high wear resistance properties of the coating [9].

Figure 6 shows the microstructure of the coating layer obtained as a result of melt coating. In part 6a of the figure, the general structure of the coated layer and the Boundary Zone with the base metal are clearly traced. In this area, it is seen that a metallurgical bond is formed between the coated layer and the base metal, which ensures the adhesive strength of the coating. Part 6b of the figure depicts the structure of the transition zone between the coated layer and the base metal. In this zone, there is a gradual change in the structure, which is associated with diffusion processes resulting from the introduction of heat and contributes to reducing the concentration of stresses. In part 6c) of the figure, solid carbide phases are clearly visible, evenly distributed throughout the Matrix. These phases are mainly chromium-rich carbides and provide high hardness and abrasion resistance of the coating. The dispersed distribution of carbide phases affects the improvement of the mechanical properties of the coating and the formation of a stable structure during Operation. The results of energodispersion X-ray microanalysis (EDX) showed that the studied coating is dominated by Iron (Fe) as the main element, as well as Silicon (Si) and a small amount of other alloying elements. It has been found that in most spectra, the iron content reaches the range of 90-98%, which proves the formation of an iron-based structure in the molten coating layer. The presence of silicon and other elements is associated with the chemical composition of the powder wire used and contributes to increasing the hardness and wear resistance of the coating [10,11, 12].



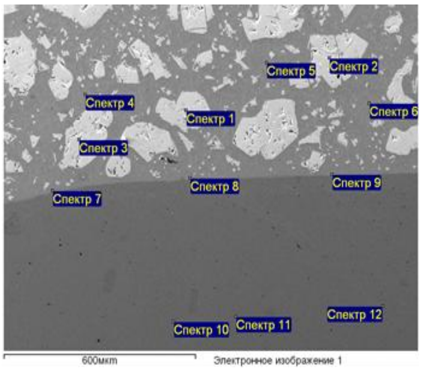
Спектр	В стат.	Si	Cr	Mn	Fe	Итог
Спектр 1	Да	1.74	5.57	0.84	91.85	100.00
Спектр 2	Да	1.88	5.52	0.72	91.88	100.00
Спектр 3	Да	1.81	6.14	1.01	91.04	100.00
Спектр 4	Да	1.51	4.12	1.00	93.37	100.00
Спектр 5	Да	1.24	4.89	0.71	93.16	100.00
Спектр 6	Да	1.48	4.52	0.73	93.27	100.00
Спектр 7	Да	0.15	0.00	0.82	99.03	100.00
Спектр 8	Да	0.17	0.00	0.83	99.00	100.00
Спектр 9	Да	0.00	0.00	0.42	99.58	100.00
Среднее		1.11	3.42	0.79	94.69	100.00
Станд. отклонение		0.78	2.63	0.17	3.48	
Макс.		1.88	6.14	1.01	99.58	
Мин.		0.00	0.00	0.42	91.04	

a)



Спектр	В стат.	Si	Cr	Mn	Fe	Mo	Итог
Спектр 1	Да	0.86	31.55		63.86	3.72	100.00
Спектр 2	Да	0.79	38.63		56.95	3.63	100.00
Спектр 3	Да	1.04	22.48		74.25	2.23	100.00
Спектр 4	Да	0.63	7.30	0.53	90.83	0.71	100.00
Спектр 5	Да	0.69	13.09	0.00	84.97	1.25	100.00
Спектр 6	Да	0.76	15.16	0.00	82.72	1.36	100.00
Спектр 7	Да	0.00		2.05	97.95		100.00
Спектр 8	Да	0.34		0.49	99.17		100.00
Спектр 9	Да	0.31		0.77	98.92		100.00
Макс.		1.04	38.63	2.05	99.17	3.72	
Мин.		0.00	7.30	0.00	56.95	0.71	

b)



Спектр	В стат.	Si	Ti	Mn	Fe	Ni	W	Итог
Спектр 1	Да						100.00	100.00
Спектр 2	Да						100.00	100.00
Спектр 3	Да						100.00	100.00
Спектр 4	Да		2.86		10.90	62.55	23.69	100.00
Спектр 5	Да	0.88			16.82	76.41	5.88	100.00
Спектр 6	Да				15.26	78.85	5.89	100.00
Спектр 7	Да				39.14	54.96	5.90	100.00
Спектр 8	Да				31.43	61.23	7.35	100.00
Спектр 9	Да				52.49	47.51		100.00
Спектр 10	Да			1.41	98.59			100.00
Спектр 11	Да			1.78	98.22			100.00
Спектр 12	Да			1.53	98.47			100.00
Макс.		0.88	2.86	1.78	98.59	78.85	100.00	
Мин.		0.88	2.86	1.41	10.90	47.51	5.88	

c)

Fig7. - SEM-images of characteristic areas of molten-coated layers and local EDS-analysis points are shown: a) EnDOtec DO351, b) DO332 and c) DO*11.

Figure 7 presents the results of Energodispersion (EDS) spectral analysis aimed at determining the chemical composition of the molten coating layer. For samples obtained using EnDOtec DO351 wire, the iron-based composition was found to prevail. At individual analysis points, the silicium content is 0-1.88 wt.%, Chromium-0-6.14 wt.%, manganese-0.42-1.01 wt.% of iron as the main component is 91.04–99.58 wt.% observed in the % range. Average estimated values Si – 1.11 wt.%, Cr - 3.42 wt.%, Mn - 0.79 wt.% and Fe - 94.69 wt.%. These indicators mean that the coating has a relatively homogeneous structure and a low level of alloying [13].

In coatings obtained on the basis of EnDOtec DO332 wire, a pronounced unevenness of the elemental composition was recorded. In particular, the chromium content varied between 7.30 to 38.63 wt.%, molybdenum fluctuates from 0.71 to 3.72 wt.%, and iron varied from 56.95 to 99.17 wt.%. At the same time, the manganese content reached up to 2.05 wt.%. Such differences indicate that areas with varying degrees of alloy are formed in the coating layer. This phenomenon is explained by the specificity of the DO332 wire, that is, the formation of an austenitic Matrix and the presence of chromium and Cr–Mo carbides in it. However, it should be noted that the EDS method used does not allow to fully determine the exact nature of the phases.

The highest heterogeneity of the chemical composition was observed in the samples obtained on the basis of the endotec do11 wire. In some regions, the tungsten content is significantly higher, varying within the range of 5.88–23.69 wt.%. At the same time, the proportion of iron ranged from 47.51 to 78.85 wt.% and manganese varied between 10.90 and 52.49 wt.%. In layers close to the base metal, the iron content increased to 98.22–98.59 wt.%, manganese emained at the level of 1.41–1.78 wt.%. These results show that there are tungsten-rich solid phases in the coating structure and that the composition gradually changes in thickness (gradient character). Such a feature corresponds to the chemical and structural properties of the wire DO11 used.

The studies carried out have shown that melt coating technology allows you to form a stable and high-quality coating that has the necessary structural and mechanical characteristics. The results obtained prove that the presented materials can be effectively used in increasing the wear resistance of the working bodies of mining machines.

According to the data presented in Table 3, the highest micro-strength indicator was recorded in sample №3 (EnDOtec DO351) with a value of 1705 HV0.1, which is explained by the high strength of the initial solid carbide phases. At the same time, the microhardness of the matrix area is approximately at the level of 445 HV0.1, providing sufficient viscosity of the material and resistance to impact loads. In samples №1 (671.4 HV0.1) and №2 (625.7 HV0.1), it was found that the average hardness of the coating layer is several times higher compared to the base material (C45 steel, about 200 HV0.1).

Table 3. Results of micro-strength measurements of Melt-coated samples ($HV_{0.1}$)

Example	Melting plating material	Microhardness of the Matrix near the sewing area $HV_{0.1}$	Micro-strength of the melt-coated layer $HV_{0.1}$	Explanation
№1	EnDOtec DO*11	320.7	671.4	Average hardness of molten coated metal
№2	EnDOtec DO*332	310.2	625.7	Average hardness of molten coated metal
№3	EnDOtec DO*351	248.0	1705.0	Solid carbide phase measurement (Cr_7C_3)

Conclusion

The results of the conducted study showed that melt-coated coatings formed using GMAW technology, implemented in a protective gas environment, significantly increase the wear resistance of Rotary mining tools.

As a result of metallographic analysis, it was found that a heterogeneous structure was formed in the coating layer, characterized by a uniform distribution of the matrix and solid carbide phases. The gradual change of structure in the transition zone ensures a strong metallurgical bond between the base metal and the coating.

The results of the energo-dispersion spectral analysis showed that the coating contains iron, chromium, tungsten and other alloying elements, ensuring high hardness and resistance to abrasive wear of the coating.

It was found as a result of micro-hardness measurements, that the hardness of the melt-coated layer is several times higher than that of the base metal. The highest value reaches the level of 1705 HV0.1, and it has been proven that this is associated with the formation of carbide phases.

Thus, the use of GMAW technology makes it possible to extend the service life of Rotary mining knives, increase the reliability of their operation and reduce production costs. The presented technology is suitable for use in industrial conditions and appears to provide a cost-effective solution.

This study will be continued, and in-depth analysis of its results plus scientifically substantiated conclusions will be presented in full in the doctoral dissertation work of Kapkenova M. T.

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