

RESTORATION OF THE IMPACT CRUSHER ROTOR USING FCAW WITH HIGH-MANGANESE STEEL REINFORCED BY COMPLEX CARBIDES

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Abstract:

A new hardfacing alloy within the Fe-Ti-Nb-Mo-V-C alloying system was utilized to restore the working surfaces of cone crusher rotors using Flux-Cored Arc Welding (FCAW). TiC, NbC, Mo₂C, VC, Mn, and ferromanganese powders were selected as the base materials for manufacturing the welding wire. The resulting hardfaced layer exhibits a composite structure, with manganese austenite as the matrix and complex solid solution reinforcements with a NaCl structure, closely resembling the formula (Ti_{0.3}Nb_{0.3}Mo_{0.3})C. The primary advantages of this hardfacing alloy include its capacity for intensive deformation hardening along with high abrasion resistance. The hardness of the hardfaced layer is approximately 47 HRC in the as-deposited state and increases to around 57 HRC after work hardening, surpassing typical hardfacing alloys derived from high manganese steel by about 10 HRC. The efficacy of the alloy was tested in restoring rotors made of Hadfield steel in a PULVOMATIC series crusher model 1145, during the milling of sand-gravel mixtures ranging from 25 to 150 mm into spalls measuring 5 to 20 mm. With an average productivity of approximately 60 tons per hour and a production volume of 300 tons, the utilization of this hardfacing alloy enabled multiple restorations of the rotor while maintaining productivity at a level of 15 thousand tons of spalls.

Key words: abrasion wear, hardfacing, high-manganese steel, impact crusher, refractory compounds

INTRODUCTION

Any construction regardless of its type – a new one or reconstruction of buildings, construction or repair of roads is always accompanied by the consumption of significant volumes of construction materials. At the same time, construction is one of the largest sources of waste in Ukraine and the world. These wastes include concrete, bricks, asphalt, soil, etc., and their processing allows for obtaining valuable secondary materials that can be reused in civil and industrial construction, road construction, and other industries. In particular, it is possible to obtain high-quality coarse aggregates for the production of concrete mixture from processed from the demolition or destruction of buildings and structures. The obtained secondary aggregates can be used as a partial or complete replacement

of natural aggregates, contributing to the development of a circular economy and reducing the consumption of natural mineral resources. Therefore, managing the production of new construction materials and recycling waste from the construction and road industries is of primary importance to reduce the burden on the environment, as well as to obtain valuable secondary raw materials that can be reused in new construction projects. One of the urgent tasks, the solution of which will allow the implementation of the strategy of sustainable development, is the rational crushing of rocks to obtain construction materials and the processing of construction waste, and this requires the development of both new specialized equipment for effective crushing and the restoration of worn out ones. The article presents the results of strengthening

and testing the rotor of the crusher, restored by electric arc welding of the coating from the developed tungsten-free alloy, directly at the place of operation of the crusher in the quarry. The work ends with conclusions relating exclusively to the results of rotor wear tests, as well as a several of modern literary references.

LITERATURE REVIEW

Today, cone crushers of various sizes and modifications are widely used during the production of building materials by crushing rocks and processing waste from industrial, civil, and road construction [1, 2, 3]. This technique is especially relevant for the implementation of strategies for effective management of waste generated in connection with the destruction of buildings and structures as a result of military operations, man-made accidents, natural disasters and natural phenomena, etc. [4, 5] thereby ensuring a reduction of environmental pollution [6, 7]. One of the main problems during the operation of equipment for crushing rocks and construction waste is that their main nodes are subjected to large dynamic loads, which lead to intensive shock-abrasive wear [8, 9], degradation [10] and fatigue damage of workers elements of parts with the formation of cracks [11].

Papers [12, 13] investigated the stress-strain state of two-layer coatings formed on a steel base under the action of an arbitrarily oriented local load. In the article [14] an assessment of the strength of the layered composition was carried out, taking into account the contact interaction of heterogeneous layers under axial load. The mechanical interaction of hard alloy coatings with fixed and unfixed abrasive was studied in [15]. The effect of non-contrast surfacing on the effectiveness of healing surface cracks in solids was studied in papers [16, 17, 18]. The authors of the articles [19, 20, 21] also note the positive role of composite layered and functional-gradient coatings in preserving the structural integrity of damaged thin-walled structures, which in particular include rotors.

Engineers and technologists use several design, technological and operational measures to reduce the harmful effects of rotor wear and destruction on the production process. The first approach consists of optimizing the design parameters of the crusher, in particular the shape and profile of the working bodies and bearing assemblies [22], ensuring effective lubrication of the bearing supports of the rotors [23, 24] and reliable connection of the rotors with their drives [25]. The development of rational routes [26], the choice of processing modes of functional surfaces and equipment [27, 28, 29] to ensure the accuracy and quality of working surfaces [30, 31, 32] plays an important role during the manufacture of new parts for the restoration of worn parts of machines and equipment. Special attention is paid to careful static and dynamic balancing of rotors [33, 34]. Recently there was published a paper [35] on optimal control for rotor imbalance suppression. The authors presented a system of moving balancing masses and evaluated the optimal displacement of the balancing masses to minimize the imbalance on the rotor. The optimal displacement is given by open-loop

control, which solves the optimal control problem posed in infinite time. The existence of an optimum is proved using the methods of calculus of variations and the corresponding optimality conditions are derived. The asymptotic behavior of the control system is rigorously investigated. Using Loyasevich's inequality, the optimums converge with time $t \rightarrow +\infty$ to a stable configuration. An explicit estimate of the convergence rate is given. This ensures that the optimal control stabilizes the system. In the case, when the imbalance is less than the calculated threshold, convergence is exponentially fast. Using the slice function and the directional derivative, as in [36, 37], we can consider the optimal control problem for rotor imbalance in any direction, not just along the real axis.

The phenomenon of severe vibration is common during crushing operation, and its vibration comes from many sources, primarily from the high-speed rotating impact of the cutting mechanism during stone shredding and rock drilling [38]. Due to the structural shape and intermittent and uneven cutting, shredder vibration is a real problem that can only be optimized but cannot be completely avoided.

Modal analysis is an effective method for studying the vibration characteristics of a structure and is the basis for dynamic analysis. The universal mechanical equation for the dynamics of the object is justified in [39]:

$$[M]\{\ddot{x}\} + [C]\{\dot{x}\} + [K]\{x\} = \{F(t)\}$$

where:

$[M]$, $[C]$, $[K]$ are the quality, damping, and stiffness matrices, respectively,

$\{F(t)\}$ is the force vector,

$\{x\}$, $\{\dot{x}\}$, $\{\ddot{x}\}$ are the displacement, speed, and acceleration vectors, accordingly.

It is the system of second-order linear non-homogeneous differential equations. Its exact solutions are given as entire curves [40, 41] represented by a sum of exponential polynomials and a partial vector-valued solution generated by the non-homogeneous part, i.e. the force matrix. Moreover, the curves have interesting local and asymptotic properties as functions having bounded index in direction [36, 37]. Therefore, it is advisable to equip crushers with modern anti-vibration devices and dampers of various designs to minimize the harmful effects of dynamic loads on their parts and assemblies [42, 43, 44].

No less important are also preventive measures, i.e. the introduction of modern innovations in the management of the mining industry [45, 46], quality management [47] of intelligent computer control systems [48] of diagnostics and monitoring of the technical condition of crushers, which make it possible to detect signs of wear in advance [49] and plan timely repairs, including in production conditions [50].

The application of technologies for the repair of equipment in industry [51] and the use of wear-resistant materials to strengthen their working surfaces during the manufacture and repair of parts that are subject to intensive wear [52, 53, 54] allows you to significantly save steel, which is relevant in view of the current state of their production [55]. In this direction, the application of

smoothing treatment even at the stage of obtaining workpieces of parts such as bodies of rotation by centrifugal casting with tungsten carbide reinforcement of the working zone provides a significant increase in wear resistance [56]. However, the high cost of tungsten carbide holds back the widespread adoption of this technology in production.

Typical materials used in alloys to ensure impact-abrasive wear resistance include tungsten carbide phases (WC and W_2C). However, the cost of raw materials for obtaining tungsten carbide phases has significantly increased over the past decades and shows a further upward trend. WC-based materials, due to their versatility, are widely used in various industries such as material processing, oil and gas equipment, mining machinery, cermets, wear-resistant alloys, and coatings. In the latter case, the use of tungsten materials is not always justified, as several transition metal compounds demonstrate comparable or higher microhardness alongside relatively low cost according to data from the United States Geological Survey (USGS) [57] (see Fig. 1).

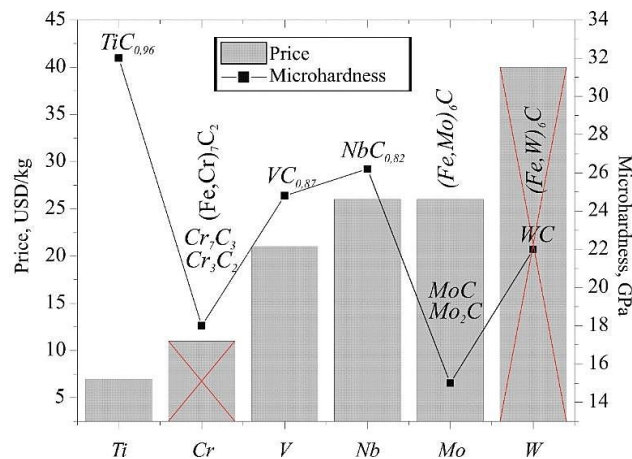


Fig. 1 Comparative characteristics of the cost of refractory metals used in hardfacing alloys and the hardness of their carbide phases

Furthermore, tungsten carbides interact intensively with the melt of high-manganese steel, leading to the formation of complex carbide phases such as $(W, Fe, Mn)_6C$. High-chromium alloys, as an alternative to tungsten materials, are not rational for use under impact-abrasive wear conditions due to their low toughness resistance. Another effective improvement in repair technology is, in particular, the use of new tungsten-free alloys for the restoration of worn surfaces of parts by surfacing. Theoretical approaches to the development of such new compositions of wear-resistant alloys are considered in papers [58, 59, 60, 61]. The authors [62, 63] investigated the influence of the filling factor of powder electrodes and exothermic applications on stable arc combustion during electric arc welding of coatings with powder electrodes.

In the paper [64] it is proposed to use oxygen-acetylene powder surfacing of self-fluxing NiCrSiB powders to prevent wear of cast iron. It was established that the amount of weight wear of the NiCrSiB alloy is smaller than the

reference samples from X5CrNi18-10 and EN-GJL-200. To increase the wear resistance of low-carbon steel and gray cast iron, researchers [65] proposed forming composite layers of the TiC/Fe type using self-propagating high-temperature synthesis, which are characterized by high resistance to various types of wear.

The proposed measures make it possible to increase the abrasive wear resistance [63, 66] and impact-abrasive wear resistance of steels [64, 65, 67, 68], which ensures the extension of the service life of various steel parts. The results of research [66, 67, 69, 70] indicate the prospects of using tungsten-free alloys for electric arc surfacing of working elements of rotors of expensive equipment for crushing rocks and destroyed building elements.

The purpose of the research is to develop a technology for restoring worn surfaces of cone crusher rotors with a tungsten-free alloy.

To achieve the goal, the following tasks must be solved:

- examine the worn rotors of the cone crusher;
- to develop an alloy of Fe-Ti-Nb-Mo-V-C alloying system and rotor restoration technology;
- conduct industrial tests of restored cone crusher rotors.

MATERIALS AND METHODS

Based on this, the primary starting materials for obtaining alloys of the "high-manganese steel – carbide" system were refractory carbides NbC (TU 6.09.03.6-75), TiC (TU 6.09.492-75, TU 6.09.03.427-76 (pseudo-alloyed titanium carbide)), VC (TU 6.09.03.5-75), and Mo_2C (TU 6.09.03.363-75), the morphology of which is depicted in Fig. 2.

As observed in the figure, the initial NbC particles are characterized by a shape close to spherical and an average size of approximately 1 μm (Fig. 2a). The pseudo-alloyed TiC (Fig. 2b) and Mo_2C carbides used were characterized by angular shapes and sizes ranging from about 50 to 100 μm , while VC powders comprised both dispersed particles and conglomerates up to 200 μm in size. Carbide phases with this particle size distribution allow for a high level of manufacturability in the production of powder electrode materials. Considering that the use of exclusively fine-dispersed powders does not provide the necessary level of flowability to achieve a high level of powder strip filling coefficient, the chosen carbide sizes are advantageous. To ensure the required manganese content, a combination of Mn powders (grade MN997 (GOST 6008-90)) and ferrosilicomanganese grade MNS17 (GOST 4756-91, ISO 5447-80), produced by PJSC "Nikopol Ferroalloy Plant", Ukraine, was used for alloying.

The technological process of producing powder strips was conducted at MNVC "Epsilon LTD", Ukraine, using a stand for manufacturing electrode materials (Fig. 3a) in the form of single-lock powder strips (Fig. 3b).

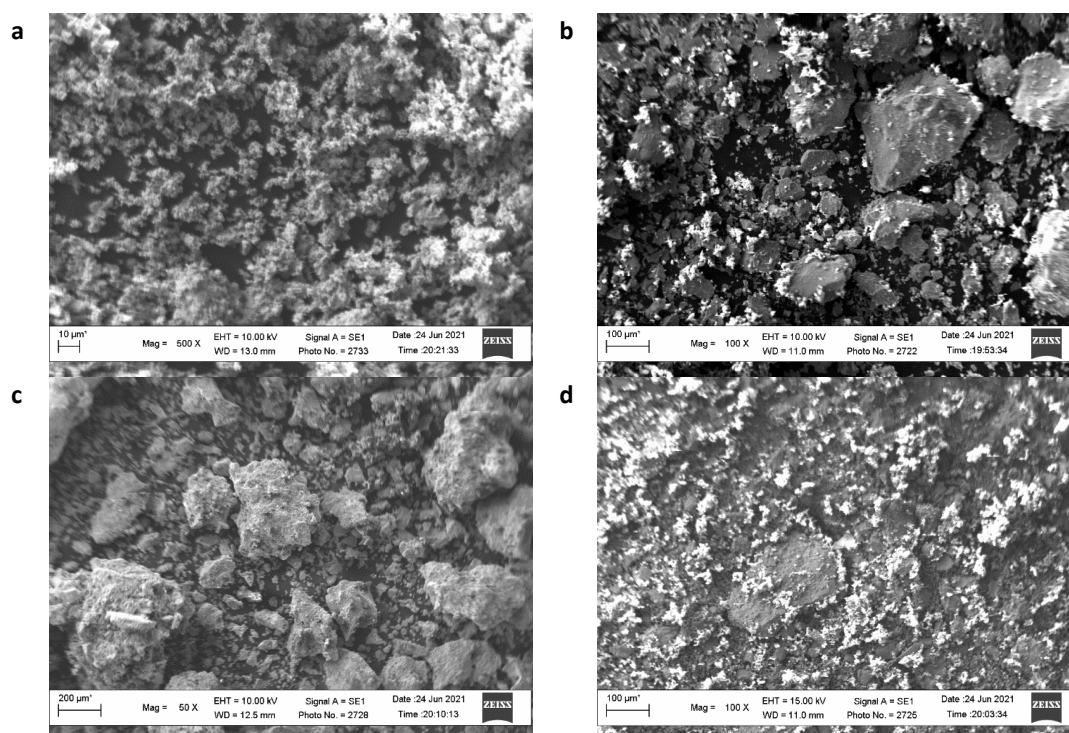


Fig. 2 Morphology of carbide phase powders used for the production of experimental hardfacing alloys:
a – NbC, b – TiC, c – VC, d – Mo₂C

The stand for manufacturing electrode materials consists of a dispenser for controlled delivery of the powder mixture (item 1, Fig. 3a), forming rollers (item 2, Fig. 3a), rollers for feeding strips of low-carbon steel 08kp (DSTU EN 10139:2018) with a width of 20 mm and a thickness of 0.5 mm (item 3, Fig. 3a), a mechanism for feeding the core from the powder strip (if necessary) (item 4, Fig. 3a), exhaust ventilation (item 5, Fig. 3a), control unit (item 6, Fig. 3a), and cutters for cutting the strip into electrodes with a length of 400 mm (if necessary).

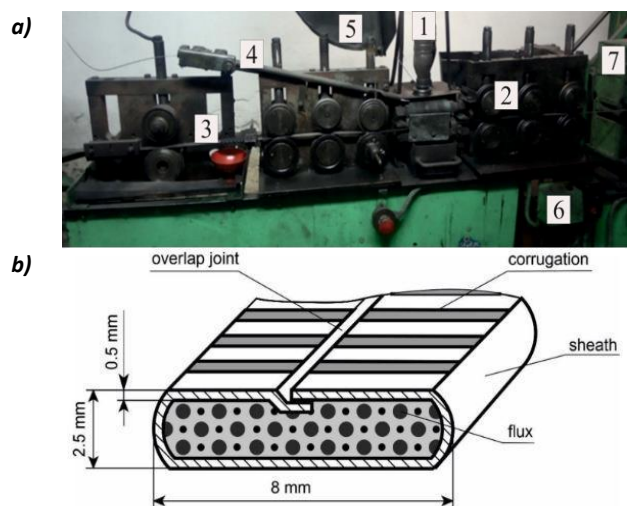


Fig. 3 Stand for manufacturing powder strips (as labelled in the text) (a) and its construction (b)

Considering the constraints imposed by the design of powder electrode materials (the powder content of carbide phases), the optimal elemental composition of the hardfacing alloy for the "high-manganese steel – multi-

component carbide" system will correspond to that outlined in Table 1 and marked as 360G15M6B6T3C3F.

Table 1
Composition of the alloy for hardfacing in the "high-manganese steel – multi-component carbide" system

The content of components in the hardfacing alloy 360G15M6B6T3C3F, wt. %							
Fe	Mn	Mo	Nb	Ti	V	C	Si
61	15.5	6.4	6.2	3.2	0.8	3.6	3.3

Based on macrohardness measurements using Leeb's dynamic hardness testing method and Rockwell surface hardness indentation, the hardness of the deposited layer with this alloy is approximately 47 HRC after deposition and approximately 57 HRC after deformation strengthening. A Fe-Ti-Nb-Mo-V-C alloy was developed to restore the worn surfaces of the cone crusher rotors. FCAW surfacing mode: direct current 170 A with reverse polarity and arc voltage 30-32 V. Power source – rectifier VDU-506. The deposited coatings were manually applied to the rotor blade in industrial conditions in several layers. Cooling of the welded coating was carried out in air at an ambient temperature of 20°C.

The microstructure and element distribution of the hardfaced layer were determined by scanning electron microscopy (SEM) together with energy-dispersive X-ray spectroscopy (EDS) using scanning electron microscope ZEISS EVO 40XVP (ZEISS Group, Jena, Germany) with a micro X-ray spectral analysis system and an INCA ENERGY 350 (Oxford Instruments, Abingdon, UK) energy dispersive X-ray spectrometer.

RESULTS AND DISCUSSION

The necessity to intensify infrastructure reconstruction efforts in Ukraine during both wartime and post-war periods requires the application of a wide range of equipment for the production of construction materials, including foreign-made equipment designed for operation in challenging conditions. Among such equipment are impact crushers from the PULVOMATIC series crusher model 1145 (Spain) (Fig. 4a), designed for crushing a wide range of materials such as gravel, crushed stone, concrete, etc. The main working element of these crushers is a multi-section rotor made of Hadfield steel using casting methods (Fig. 4b).

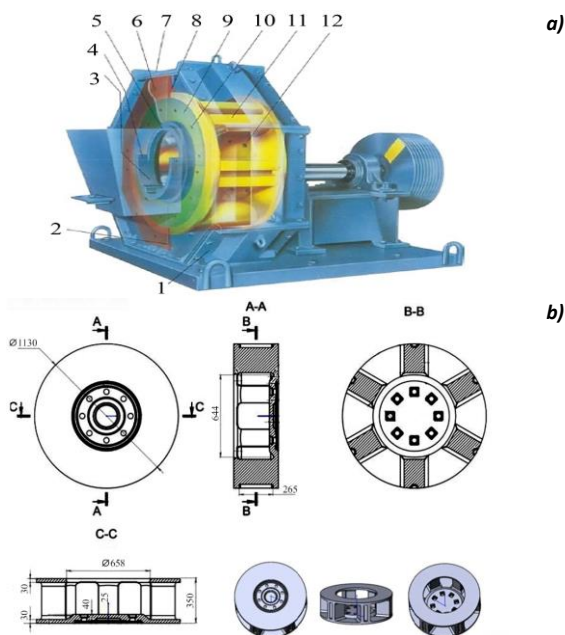


Fig. 4 Structure of the PULVOMATIC series crusher model 1145 (a) and its main working element – the rotor (b):

1 – lower crushing palte; 2 – bottom lining; 3 – lower bushing; 4 – lip screw; 5 – upper bushing; 6 – liner screw; 7 – top break plate; 8 – upper lining; 9 – wear plate; 10 – wear plate screw; 11 – rotor; 12 – rotor screw

Source: [71].



Fig. 5 General view of PULVOMATIC series crusher model 1145 (a), raw material (b), and finished product (c)

The analysis of the operation of the PULVOMATIC series crusher model 1145 (Fig. 5a) at a rotor rotation frequency of 1500 rpm during the crushing of a sand-gravel mixture with an initial particle size distribution of 25-150 mm (Fig.

5b) to produce gravel with a primary final particle size distribution of 5-20 mm (Fig. 5c) revealed an average processing capacity of approximately 60 t/hour, with an operating period exceeding 300 hours.

The results indicate significant wear of the rotor's working surfaces under these conditions, leading to the catastrophic impact-abrasive wear (Fig. 6), which is the cause of fatigue failure of the rotor at weakened areas and, consequently, the occurrence of potentially hazardous situations.



Fig. 6 Character of catastrophic wear of the rotor of the PULVOMATIC series crusher model 1145

Considering that the cost of a new rotor is approximately €6000, and taking into account additional expenses related to logistics, ensuring the profitability of operating this crushing equipment in the conditions of Ukraine requires a more optimal approach. Moreover, material costs associated with equipment downtime due to complicated logistics, especially during wartime, are an additional factor negatively impacting production profitability. Therefore, it was proposed to reduce the volume of processed raw materials from 20 to 15 thousand tons, i.e., to conditions where catastrophic wear does not occur. Under these conditions, the wear of the working surfaces (Fig. 7a) allows for multiple restoration of the working surfaces using the hardfacing method (Fig. 7b) by using the developed alloy Fe-Ti-Nb-Mo-V-C to restore the worn surfaces of the rotors of cone crushers. It should be noted that after the restoration of worn rotors, it is necessary to balance the rotors, including in production conditions.

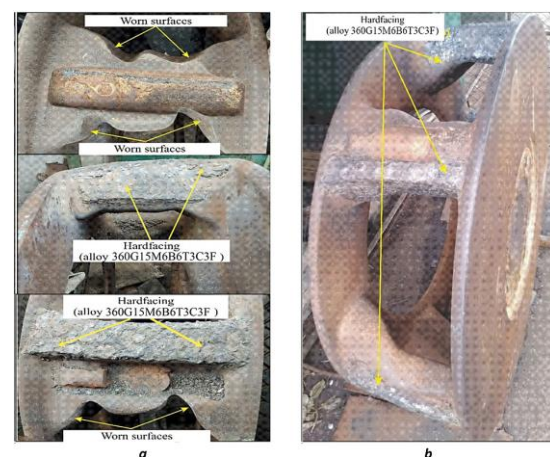


Fig. 7 Worn and restored sections of the rotor of the PULVOMATIC series crusher model 1145 (a) and the overall appearance of the rotor after restoring the geometry of worn surfaces (b)

The deposited layer (Fig. 8) consists of an austenite matrix reinforced with a complex carbide solid solution corresponding to the formula $(\text{Ti}_{0.3}\text{Nb}_{0.3}\text{Mo}_{0.3})\text{C}$, which is uniformly distributed within the steel matrix in the form of grains with cuboidal morphology. The average size of the carbide grains is $\sim 3\ \mu\text{m}$, and their microhardness is higher than 20 GPa. The EDS analysis of the fusion zone shows a smooth transition from the base material to the hardfaced layer. Defects like pores, cracks, and delamination were not observed, indicating strong metallurgical bonding. In the regions corresponding to the carbide inclusions, simultaneous peaks of the carbide-forming elements were detected, indicating the presence of a solid solution. The obtained composite structure of the hardfaced layer creates prerequisites for the combined deformation and dispersion strengthening of the surface layer during impact loads in abrasive environments.

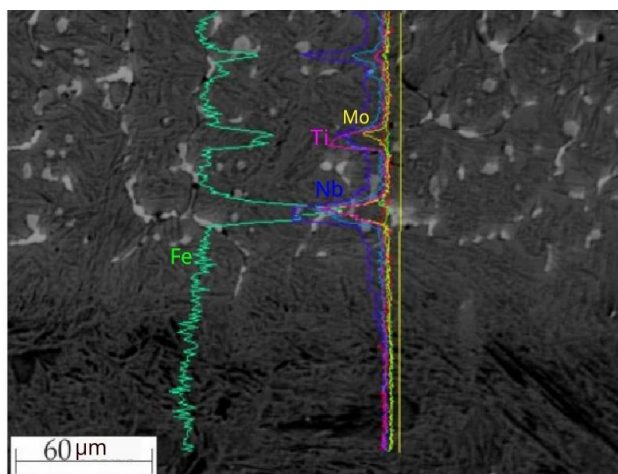


Fig. 8 The microstructure and results of the EDS analysis of the fusion zone of the hardfaced layer with 360G15M6B6T3C3F alloy

In further studies, it is planned to optimize the technological regimes of flux-cored arc welding rotors.

CONCLUSIONS

As a result of the analysis of the working conditions and examination of the rotors of the cone crusher, it was established that the main reasons for their failure are shock-abrasive wear and fatigue failure.

The results of industrial tests showed high wear resistance of the deposited coating from the developed Fe-Ti-Nb-Mo-V-C alloy system and its industrial suitability for restored cone crusher rotors.

Our developed technology allows us to perform restoration work directly at the crushers' operation site, reducing non-productive downtime. This is particularly important due to the increasing demand for raw materials needed for producing construction products essential for the reconstruction of Ukraine's industrial and civil infrastructure.

ACKNOWLEDGEMENTS

The authors express their sincere gratitude and respect to the Armed Forces of Ukraine, who made it possible to complete the preparation of this article for publication. The authors also express their gratitude to the Ministry of Science and Education of Ukraine for grants for the implementation of projects 0123U101858 and 0124U000668. The team of authors express their gratitude to the reviewers and academic editor for valuable recommendations that have been taken into account to significantly improve the quality of this paper. The article was made as part of the research subsidy 16.16.130.942/KSW.

REFERENCES

- [1] Z. Zhang, T. Ren, J. Cheng and J. Zhu. "An Improved Capacity Model of the Cone Crushers Based on the Motion Characteristics of Particles Considering the Influence of the Spatial Compound Motion of the Mantle." *Minerals*, vol. 12, art. no. 235, 2022. <https://doi.org/10.3390/min12020235>
- [2] S. Wu, S. Wang, G. Wang, L. Fan, J. Guo, Z. Liu, H. Zhang, W. Guan, Y. Wang and Y. Wu. "Study on productivity of eccentric roll crusher based on theory and experiment." *Minerals Engineering*, vol. 206, art. no. 108500, 2024. <https://doi.org/10.1016/j.mineng.2023.108500>
- [3] M. Bembenek and P. Wdaniec. "Effect of crusher type and its parameters on the dry granulation of powders [Wpływ rodzaju kruszarki oraz parametrów jej pracy na suchą granulację proszków]." *Przemysł Chemiczny*, vol. 98, pp. 310-313, 2019. <https://doi.org/10.15199/62.2019.2.25>
- [4] R. Haigh. "A Decade Review of Research Trends Using Waste Materials in the Building and Construction Industry: A Pathway towards a Circular Economy." *Waste*, vol. 1, pp. 935-959, 2023. <https://doi.org/10.3390/waste1040054>
- [5] S. Kurnosov, L. Ropyak, A. Velychkovych, T. Pryhorovska and V. Vytvytskyi. "Mechanical – Insulating Method of Household and Industrial Waste Utilization," in *New Technologies, Development and Application IV. NT 2021. Lecture Notes in Networks and Systems*, vol. 233. I. Karabegović, Ed. Cham: Springer, 2021, pp. 431-441. https://doi.org/10.1007/978-3-030-75275-0_48
- [6] M. Korchemlyuk and L. Arkhypova. "Environmental Audit of Ukrainian Basin Ecosystem of the Prut River." *Naukovyi Visnyk Natsionalnoho Hirnychoho Universytetu*, vol. 2016, pp. 97-106, 2016.
- [7] W. Bialy, W. Grebski, G. Galecki and W. Kaniak. "Environmental impact of the mechanical coal processing plant." *Acta Montanistica Slovaca*, vol. 25, pp. 139-149, 2020. <https://doi.org/10.46544/AMS.v25i2.1>
- [8] D. Li, Y. Wang, C. Wang and S. Li. "Research on the Wear Behavior of the Fixed Cone Liner of a Cone Crusher Based on the Discrete Element Method." *ACS Omega*, vol. 5, art. no. 16, 2020. <https://doi.org/10.1021/acsomega.0c01272>
- [9] Z. Zhang, T. Ren and J. Cheng. "Constant Wear Criterion for Optimization of the Crushing Chamber of Cone Crushers." *Minerals*, vol. 12, art. no. 807, 2022. <https://doi.org/10.3390/min12070807>
- [10] H.M. Nykyforchyn, O.T. Tsyryl'nyk, D.Yu. Petryna, and M.I. Hredil'. "Degradation of steels used in gas main pipelines during their 40-year operation." *Strength of Materials*, vol. 41, pp. 501-505, 2009. <https://doi.org/10.1007/s11223-009-9158-8>
- [11] Z.M. Rykavets, J. Bouquerel, J.-B. Vogt, Z.A. Duriagina, V.V. Kulyk, T.L. Tepla, L.I. Bohun and T.M. Kovbasyuk.

- "Investigation of the microstructure and properties of trip 800 steel subjected to low-cycle fatigue." *Progress in Physics of Metals*, vol. 20, pp. 620-633, 2019. <https://doi.org/10.15407/ufm.20.04.620>
- [12] L. Ropyak, I. Shatskyi and M. Makoviichuk. "Influence of the oxide-layer thickness on the ceramic-aluminium coating resistance to indentation." *Metallfizika i Noveishie Tekhnologii*, vol. 39, pp. 517-524, 2017. <https://doi.org/10.15407/mfint.39.04.0517>
- [13] I.P. Shatskyi, L.Y. Ropyak and M.V. Makoviichuk. "Strength optimization of a two-layer coating for the particular local loading conditions." *Strength of Materials*, vol. 48, pp. 726-730, 2016. <https://doi.org/10.1007/s11223-016-9817-5>
- [14] L. Ropyak, T. Shihab, A. Velychkovych, O. Dubei, T. Tutko and V. Bilinskyi. "Design of a Two-Layer Al-Al₂O₃ Coating with an Oxide Layer Formed by the Plasma Electrolytic Oxidation of Al for the Corrosion and Wear Protections of Steel." *Progress in Physics of Metals*, vol. 24, pp. 319-365, 2023. <https://doi.org/10.15407/ufm.24.02.319>
- [15] L. Ropyak, I. Shatskyi and M. Makoviichuk. "Analysis of interaction of thin coating with an abrasive using onedimensional model." *Metallfizika i Noveishie Tekhnologii*, vol. 41, pp. 647-654, 2019. <https://doi.org/10.15407/mfint.41.05.0647>
- [16] I.P. Shats'kyi. "Limiting equilibrium of a plate with partially healed crack." *Materials Science*, vol. 51, pp. 322-330, 2015. <https://doi.org/10.1007/s11003-015-9845-5>
- [17] I.P. Shatskyi, V.V. Perepichka and L.Y. Ropyak. "On the influence of facing on strength of solids with surface defects." *Metallfizika i Noveishie Tekhnologii*, vol. 42, pp. 69-76, 2020. <https://doi.org/10.15407/mfint.42.01.0069>
- [18] T.M. Dalyak and I.P. Shatsky. "On brittle fracture of a body with partial healed star-shaped crack." *Bulletin of Taras Shevchenko National University of Kyiv. Physical and Mathematical Sciences*, vol. 2023, pp. 100-103, 2023. <https://doi.org/10.17721/1812-5409.2023/2.13>
- [19] I.P. Shatskyi, M.V. Makoviichuk and A.B. Shcherbii. "Equilibrium of Cracked Shell with Flexible Coating," in *Shell Structures: Theory and Applications – Proceedings of the 11th International Conference on Shell Structures: Theory and Applications, SSTA 2017, Gdansk, Poland*, vol. 4. W. Pietraszkiewicz, W. Witkowski, Ed. London: CRC Press, 2017, pp. 165-168. <https://doi.org/10.1201/9781315166605-34>
- [20] M. Dutkiewicz, T. Dalyak, I. Shatskyi, T. Venhrynyuk and A. Velychkovych. "Stress Analysis in Damaged Pipeline with Composite Coating." *Appl. Sci.*, vol. 11, art. no. 10676, 2021. <https://doi.org/10.3390/app112210676>
- [21] I. Shatskyi, M. Makoviichuk, L. Ropyak and A. Velychkovych. "Analytical model of deformation of a functionally graded ceramic coating under local load." *Ceramics*, vol. 46, pp. 1879-1893, 2023. <https://doi.org/10.3390/ceramics6030115>
- [22] V. Martsinkovsky, V. Yurko, V. Tarelnyk and Y. Filonenko. "Designing radial sliding bearing equipped with hydrostatically suspended pads." *Procedia Engineering*, vol. 39, pp. 157-167, 2012. <https://doi.org/10.1016/j.proeng.2012.07.020>
- [23] V. Kotsyubynsky, L. Shyiko, T. Shihab, P. Prysyazhnyuk, V. Aulin and V. Boichuk. "Multilayered MoS₂/C nanospheres as high performance additives to lubricating oils." *Materials Today: Proceedings*, vol. 35, pp. 538-541, 2019. <https://doi.org/10.1016/j.matpr.2019.10.021>
- [24] O.P. Gaponova, B. Antoszewski, V.B. Tarelnyk, P. Kurp, O.M. Myslyvchenko and N.V. Tarelnyk. "Analysis of the quality of sulfomolybdenum coatings obtained by electrosark alloying methods." *Materials*, vol. 14, art. no. 6332, 2021. <https://doi.org/10.3390/ma14216332>
- [25] V. Martsynkovskyy, V. Tarelnyk, I. Konoplianchenko, O. Gaponova and M. Dumanchuk. "Technology Support for Protecting Contacting Surfaces of Half-Coupling – Shaft Press Joints Against Fretting Wear," in *Advances in Design, Simulation and Manufacturing II. DSMIE 2019. Lecture Notes in Mechanical Engineering*, V. Ivanov, et al. Ed. Cham: Springer, 2020, pp. 216-225. https://doi.org/10.1007/978-3-030-22365-6_22
- [26] Y. Kusi, O. Onysko, A. Kuk, B. Solohub and V. Kopei. "Development of the Technique for Designing Rational Routes of the Functional Surfaces Processing of Products," in *New Technologies, Development and Application V. NT 2022. Lecture Notes in Networks and Systems*, vol. 472. I. Karabegović, A. Kovačević, S. Mandžuka, Ed. Cham: Springer, 2022, pp. 135-143. https://doi.org/10.1007/978-3-031-05230-9_16
- [27] A. Permyakov, S. Dobrotvorskiy, L. Dobrovolska, Y. Basova and M. Ivanova. "Computer Modeling Application for Predicting of the Passing of the High-Speed Milling Machining Hardened Steel," in *Advances in Design, Simulation and Manufacturing. DSMIE 2019. Lecture Notes in Mechanical Engineering*, V. Ivanov, et al. Ed. Cham: Springer, 2019, pp. 135-145. https://doi.org/10.1007/978-3-319-93587-4_15
- [28] Y. Danylchenko, M. Storchak, M. Danylchenko and A. Petryshyn. "Cutting Process Consideration in Dynamic Models of Machine Tool Spindle Units." *Machines*, vol. 11, art. no. 582, 2023. <https://doi.org/10.3390/machines11060582>
- [29] I. Yakovenko, A. Permyakov, M. Ivanova, Y. Basova and D. Shepeliev. "Lifecycle Management of Modular Machine Tools," in *Advanced Manufacturing Processes III. InterPartner 2021. Lecture Notes in Mechanical Engineering*, V. Tonkonogiy, V. Ivanov, J. Trojanowska, G. Oborskyi, I. Pavlenko, Ed. Cham: Springer, 2022, pp. 127-137. https://doi.org/10.1007/978-3-030-91327-4_13
- [30] T. Pryhorovska and L. Ropyak. "Machining Error Influence on Stress State of Conical Thread Joint Details," in *Proceedings of the International Conference on Advanced Optoelectronics and Lasers, CAOL, 2019-September*, art. no. 9019544, pp. 493-497, 2019. <https://doi.org/10.1109/CAOL46282.2019.9019544>
- [31] V.B. Kopei, O.R. Onysko and V.G. Panchuk. "Computerized system based on FreeCAD for geometric simulation of the oil and gas equipment thread turning." In *International Conference on Applied Sciences (ICAS)*, vol. 477, art. no. 012032, 2019. <https://doi.org/10.1088/1757-899X/477/1/012032>
- [32] K.S. Barandych, S.P. Vysloukh and V.S. Antonyuk. "Ensuring Fatigue Life of Parts During Finish Turning with Cubic Boron Nitride Tools." *Journal of Superhard Materials*, vol. 40, pp. 206-215, 2018. <https://doi.org/10.3103/S1063457618030085>
- [33] V. Lozynskyi, T. Shihab, I. Drach and L. Ropyak. "The Inertial Disturbances of Fluid Movement in the Chamber of a Liquid Autobalancer." *Machines*, vol. 12, art. no. 39, 2024. <https://doi.org/10.3390/machines12010039>
- [34] I. Drach, V. Royzman, A. Bubulis and K. Jūzėnas. "Passive balancing of the rotor with an auto-balancing device with a viscous incompressible liquid." *Mechanika*, vol. 27, pp. 45-51, 2021. <https://doi.org/10.5755/J02.MECH.23789>
- [35] M. Gnuffi, D. Pighin and N. Sakamoto. "Rotor imbalance suppression by optimal control." *Optim Control Appl*

- Meth.*, vol. 43, pp. 213-242, 2022. <https://doi.org/10.1002/oca.2780>
- [36] A.I. Bandura. "Some improvements of criteria of L-index boundedness in direction." *Matematychni Studii*, vol. 47, pp. 27-32, 2017. <https://doi.org/10.15330/ms.47.1.27-32>
- [37] A.I. Bandura. "Composition of entire functions and bounded L-index in direction." *Matematychni Studii*, vol. 47, pp. 179-184, 2017. <https://doi.org/10.15330/ms.47.2.179-184>
- [38] I. Chudyk, P. Raiter, Ya. Grydzhuk and L. Yurych. "Mathematical model of oscillations of a drill tool with a drill bit of cutting-scraping type." *Naukovi Visnyk Natsionalnoho Hirnychoho Universytetu*, vol. 2020, pp. 52-57, 2020. <https://doi.org/10.33271/nvngu/2020-1/052>
- [39] Y. Gong, L. Ren, X. Han, A. Gao, S. Jing, C. Feng and Y. Song. "Analysis of operating conditions for vibration of a self-propelled monorail branch chipper." *Agriculture*, vol. 13, art. no. 101, 2023. <https://doi.org/10.3390/agriculture13010101>
- [40] A.I. Bandura and Y.I. Savchuk. "Structure of the set of borel exceptional vectors for entire curves." *Matematychni Studii*, vol. 53, pp. 41-47, 2020. <https://doi.org/10.30970/ms.53.1.41-47>
- [41] Y.I. Savchuk and A.I. Bandura. "Asymptotic vectors of entire curves." *Matematychni Studii*, vol. 56, pp. 48-54, 2021. <https://doi.org/10.30970/ms.56.1.48-54>
- [42] V.F. Navarro Torres, J.R. Figueiredo, R.C. De La Hoz, M. Botaro and L.S. Chaves. "A Mine-to-Crusher Model to Minimize Costs at a Truckless Open-Pit Iron Mine in Brazil." *Minerals*, vol. 12, art. no. 1037, 2022. <https://doi.org/10.3390/min12081037>
- [43] M. Dutkiewicz, A. Velychkovych, I. Shatskyi and V. Shopa. "Efficient Model of the Interaction of Elastomeric Filler with an Open Shell and a Chrome-Plated Shaft in a Dry Friction Damper." *Materials*, vol. 15, art. no. 4671, 2022. <https://doi.org/10.3390/ma15134671>
- [44] A. Velychkovych, I. Petryk and L. Ropyak. "Analytical study of operational properties of a plate shock absorber of a sucker-rod string." *Shock and Vibration*, vol. 2020, art. no. 3292713, 2020. <https://doi.org/10.1155/2020/3292713>
- [45] K. Midor. "Innovation in coal mining management as an intelligent specialization." *Production Engineering Archives*, vol. 15, pp. 41-44, 2017. <https://doi.org/10.30657/pea.2017.15.10>
- [46] M. Zasadzień and J. Zarnovský. "Improvement of Selected Logistics Processes Using Quality Engineering Tools." *Management Systems in Production Engineering*, vol. 26, pp. 55-59, 2018. <https://doi.org/10.2478/mspe-2018-0009>
- [47] S.K. Gupta and J. Rosak-Szyrocka. "Quality and Value Management in Education in the Digitalization Era," in *Quality Management, Value Creation, and the Digital Economy*, 1st ed., J. Rosak-Szyrocka, J. Żywiółek M. Shahbaz, Ed. London: Routledge, 2023, pp. 167-180. <https://doi.org/10.4324/9781003404682-11>
- [48] W. Biały, and J. Fries. "Computer systems supporting the management of machines/equipment in hard coal mines. case study." *Management Systems in Production Engineering*, vol. 27, pp. 138-143, 2019. <https://doi.org/10.1515/mspe-2019-0022>
- [49] M. Bembenek, J. Krawczyk and K. Pańcikiewicz. "The wear mechanism of mill beaters for coal grinding made-up from high manganese cast steel." *Engineering Failure Analysis*, vol. 142, art. no. 106843, 2022. <https://doi.org/10.1016/j.engfailanal.2022.106843>
- [50] K.A. Abuhasel. "Machine learning approach to handle data-driven model for simulation and forecasting of the cone crusher output in the stone crushing plant." *Computational Intelligence*, vol. 37, pp. 1098-1110, 2021. <https://doi.org/10.1111/coin.12338>
- [51] B. Gajdzik. "Autonomous and professional maintenance in metallurgical enterprise as activities within total productive maintenance." *Metalurgija*, vol. 53, pp. 269-272, 2014.
- [52] L.B. Varela, G. Tressia, M. Masoumi, E.M. Bortoleto, C. Regattieri and A. Sinatora. "Roller crushers in iron mining, how does the degradation of Hadfield steel components occur?." *Engineering Failure Analysis*, vol. 122, art. no. 105295, 2021. <https://doi.org/10.1016/j.engfailanal.2021.105295>
- [53] L. Ropyak, T. Shihab, A. Velychkovych, V. Bilinskyi, V. Malinin and M. Romaniv. "Optimization of Plasma Electrolytic Oxidation Technological Parameters of Deformed Aluminum Alloy D16T in Flowing Electrolyte." *Ceramics*, vol. 6, pp. 146-167, 2023. <https://doi.org/10.3390/ceramics6010010>
- [54] M. Bembenek, P. Prisyazhnyuk, T. Shihab, R. Machnik, O. Ivanov and L. Ropyak. "Microstructure and Wear Characterization of the Fe-Mo-B-C – Based Hardfacing Alloys Deposited by Flux-Cored Arc Welding." *Materials*, vol. 15, art. no. 5074, 2022. <https://doi.org/10.3390/ma15145074>
- [55] B. Gajdzik. "Post-Pandemic Steel Production Scenarios for Poland Based on Forecasts of Annual Steel Production Volume." *Management Systems in Production Engineering*, vol. 31, pp. 172-190, 2023. <https://doi.org/10.2478/mspe-2023-0019>
- [56] L. Ropyak, I. Schuliar and O. Bohachenko. "Influence of technological parameters of centrifugal reinforcement upon quality indicators of parts." *Eastern-European Journal of Enterprise Technologies*, vol. 1, pp. 53-62, 2016. <https://doi.org/10.15587/1729-4061.2016.59850>
- [57] USGS. Available at: <http://www.bjohnsonsworld.co.uk/theriseoftheubermensch> (Accessed: 10 May 2024).
- [58] T. Shihab, P. Prisyazhnyuk, I. Semyanyk, R. Anrusyshyn, O. Ivanov and L. Troshchuk. "Thermodynamic Approach to the Development and Selection of Hardfacing Materials in Energy Industry." *Management Systems in Production Engineering*, vol. 28, pp. 84-89, 2020. <https://doi.org/10.2478/mspe-2020-0013>
- [59] P. Prisyazhnyuk and D. Di Tommaso. "The thermodynamic and mechanical properties of Earth-abundant metal ternary boride $\text{Mo}_2(\text{Fe,Mn})\text{B}_2$ solid solutions for impact and wear-resistant alloys." *Materials Advances*, vol. 4, pp. 3822-3838, 2023. <https://doi.org/10.1039/d3ma00313b>
- [60] K.H. Levchuk, T.M. Radchenko and V.A. Tatarenko. "High-temperature entropy effects in the tetragonality of the ordering interstitial-substitutional solution based on the body-centred tetragonal metal." *Metallofizika i Noveishie Tekhnologii*, vol. 43, pp. 1-26, 2021. <https://doi.org/10.15407/mfint.43.01.0001>
- [61] V. Lozynskyi, B. Trembach, M.M. Hossain, M.H. Kabir, Y. Silchenko, M. Krbata, K. Sadovyi, O. Kolomiitse and L. Ropyak. "Prediction of phase composition and mechanical properties Fe-Cr-C-B-Ti-Cu hardfacing alloys: Modeling and experimental Validations." *Heliyon*, vol. 10, art. no. e25199, 2024. <https://doi.org/10.1016/j.heliyon.2024.e25199>
- [62] B.O. Trembach, D.V. Hlushkova, V.M. Hvozdetskyi, V.A. Vynar, V.I. Zakiev, O.V. Kabatskyi, D.V. Savenok and O.Y.

- Zakavorotnyi. "Prediction of Fill Factor and Charge Density of Self-Shielding Flux-Cored Wire with Variable Composition." *Materials Science*, vol. 59, pp. 18-25, 2023. <https://doi.org/10.1007/s11003-023-00738-7>
- [63] V. Lozynskyi, B. Trembach, E. Katinas, K. Sadovyi, M. Krbata, O. Balenko, I. Krasnoshapka, O. Rebrova, S. Knyazev, O. Kabatskyi, H. Kniazieva and L. Ropyak. "Effect of Exothermic Additions in Core Filler on Arc Stability and Microstructure during Self-Shielded, Flux-Cored Arc Welding." *Crystals*, vol. 14, art. no. 335, 2024. <https://doi.org/10.3390/cryst14040335>
- [64] Ł. Szymański, E. Olejnik, J.J. Sobczak, M. Szala, P. Kurtyka, T. Tokarski, A. Janas. "Dry sliding, slurry abrasion and cavitation erosion of composite layers reinforced by TiC fabricated in situ in cast steel and gray cast iron." *Journal of Materials Processing Technology*, vol. 308, art. no. 117688, 2022. <https://doi.org/10.1016/j.jmatprotec.2022.117688>
- [65] M. Szala, M. Walczak, T. Hejwowski. "Factors Influencing Cavitation Erosion of NiCrSiB Hardfacings Deposited by Oxy-Acetylene Powder Welding on Grey Cast Iron." *Advances in Science and Technology Research Journal*, vol. 15, pp. 376-386, 2021. <https://doi.org/10.12913/22998624/143304>
- [66] E.F. Pereplotchikov, K.B. Vasylyv, V.A. Vynar, I.O. Ryabtsev and V.I. Zakiev. "Elevation of the Wear Resistance of Low-Alloy Structural Steel by Plasma-Powder Surfacing with Alloys Based on Iron, Chromium, and Nickel." *Materials Science*, vol. 54, pp. 378-386, 2018. <https://doi.org/10.1007/s11003-018-0195-y>
- [67] P. Prysyazhnyuk, O. Ivanov, O. Matvienkiv, S. Marynenko, O. Korol and I. Koval. "Impact and abrasion wear resistance of the hardfacings based on high-manganese steel reinforced with multicomponent carbides of Ti-Nb-Mo-V-C system." *Procedia Structural Integrity*, vol. 36, pp. 130-136, 2022. <https://doi.org/10.1016/j.prostr.2022.01.014>
- [68] S. Ge, Q. Wang and J. Wang. "The impact wear-resistance enhancement mechanism of medium manganese steel and its applications in mining machines." *Wear*, vol. 376-377, Part B, pp. 1097-1104, 2017. <https://doi.org/10.1016/j.wear.2017.01.015>
- [69] P. Prysyazhnyuk, M. Molenda, T. Romanyshyn, L. Ropyak, L. Romanyshyn and V. Vytvytskyi. "Development of a hardbanding material for drill pipes based on high-manganese steel reinforced with complex carbides." *Acta Montanistica Slovaca*, vol. 27, pp. 685-696, 2022. <https://doi.org/10.46544/AMS.v27i3.09>
- [70] A.S. Yamashita, A. Thivierge, and T. Euzebio. "A review of modeling and control strategies for cone crushers in the mineral processing and quarrying industries." *Minerals Engineering*, vol. 170, art. no. 107036, 2021. <https://doi.org/10.1016/j.mineng.2021.107036>
- [71] PULVOMATIC ebroadcero. Available at: <https://www.pulvomatic.com/en/home> (Accessed: 10 May 2024).

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