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Improving the crack resistance of blast furnace skips

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Abstract. The operation of the blast furnace lining is accompanied by intense abrasive and impact wear, which makes it necessary to develop iron-containing surfacing materials with a heterogeneous carbide microstructure to increase strength and wear resistance. The aim of the work was to increase the mechanical strength and durability of the lining of the blast furnace shop by optimising the structure of the deposited layers and establishing regularities between the microstructure, mechanical properties and wear resistance of the coatings. The research was carried out using electric arc surfacing on samples of 09G2S steel. Tests were conducted for hardness, impact toughness and abrasive wear, as well as microstructural analysis of the surfaced layers and assessment of the nature of crack formation after microindentation. The main results of the experimental studies show that the hardness of the deposited layers ranged from 52 HRC in SAS Global to 58 HRC in VELTEC, while the impact toughness varied from 18 J/cm^2 in Duroxite to 22 J/cm^2 in VELTEC, demonstrating an inverse relationship between hardness and impact toughness: harder layers are more prone to brittle fracture. Abrasive wear tests showed that VELTEC demonstrated the best wear resistance with a mass loss of 0.12 g and only one crack per 100 cm^2, while SAS Global had the highest number of cracks (4 per 100 cm^2) and a mass loss of 0.20 g, and Duroxite had intermediate values – 0.18 g mass loss and 3 cracks. As a result, it was found that the formation of a hypereutectic structure with an M_7C_3 carbide phase contributes to a reduction in the intensity of abrasive wear and limits the spread of microcracks. The obtained welded layers are characterised by a combination of increased hardness and sufficient impact toughness, which is critical for the operation of the lining under variable impact loads. The practical value of the results lies in the possibility of their use in the restoration and modernisation of blast furnace linings in order to increase the inter-repair resource and reduce operating costs

Keywords: welding; microstructure; wear; strength; residual stress; hardness

Introduction

In modern blast furnace production, one of the key elements of the transport system is a skip designed for the cyclical vertical movement of charge materials to the blast furnace charging device. Under operating conditions, the skip undergoes intense abrasive impact from agglomerate, coke and ore, which causes accelerated wear of its internal surfaces. To protect the skip body from premature destruction, lining in the form of removable or deposited wear-resistant elements is widely used.

One of the main reasons for the limited service life of the skip lining is crack development, which occurs due to a combination of thermal, mechanical and structural factors. As noted by S.V. Shchetynin *et al*. (2019), residual stresses generated during surfacing play a crucial role in the appearance of microcracks, which can later develop into macro-cracks and cause the deposited layer to detach. Their microstructure has a significant influence on the tendency of deposited layers

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to crack development. High-chromium iron-containing alloys, typically used for wear-resistant surfacing, form eutectic structures with M7C3-type carbides, which provide high hardness but are also characterised by increased brittleness. An alternative approach to improving the operational reliability of linings is the use of modified surfacing alloys, in which hardening is achieved due to fine boride and carbide phases. According to the findings of O. Ivanov (2020), the development of a fine-dispersed structure with a uniform distribution of reinforcing phases helps to reduce the rate of crack propagation and increase resistance to destruction. In addition to the chemical composition of the deposited material, the surfacing technology has a significant impact on the crack resistance of the lining. The study by L. Zong *et al.* (2019) established that reducing the linear thermal energy and controlling the inter-pass temperature can reduce the level of residual stresses and form a more favourable structure of the deposited layer.

Similar conclusions were provided in the paper by A. Czupryński *et. al.* (2022), where the efficiency of optimised surfacing modes for parts of metallurgical equipment was shown. An additional factor in increasing the life of the lining is the use of buffer layers between the steel base and the wear-resistant surfacing. The study by T. Varis *et al.* (2023) explored the possibility of using iron-based (Fe-based) thermal spray coatings as an alternative to standard hard coatings to protect parts from abrasive and cavitation wear. Several commercial and experimental Fe coatings applied by high velocity Oxy-Fuel and High Velocity Air-Fuel (HVAF) methods were analysed and their microstructure, hardness, and wear resistance were compared with coatings based on WC-CoCr and Cr_3C_2-NiCr. The results showed that Fe coatings generally have a lower resistance to abrasive wear due to the lower content and size of solid phases, but in cavitation erosion tests they showed good, and sometimes better, results compared to standard coatings. The researchers concluded that cavitation wear resistance is largely determined by microstructure, cohesion between layers, and the material's ability to undergo plastic deformation, rather than just hardness, and that Fe-based coatings, especially those applied by HVAF, have significant potential for use under cavitation loading conditions.

Z.T. Öztürk (2021) investigated the effect of alloying elements such as Si, Cr, B, and Ni on the microstructure and abrasive wear resistance of FE-C-Si-Cr-B-Ni deposited layers. Hardness and abrasive abrasion tests of various alloy compositions were performed, including microstructural analysis using metallography. The results showed that the introduction of Ni and Cr promotes the generation of a denser boride and carbide structure, which increases the hardness and wear resistance of coatings. C. Okechukwu *et al.* (2024) developed new ferro alloy surfaced alloys for conditions of high abrasive wear under low impact loads. A comprehensive study of mechanical properties, including hardness, impact strength, and weight loss during abrasive wear, was conducted. The study showed that the optimal composition of the alloy provides a balance between high wear resistance and sufficient impact strength, which makes it suitable for industrial applications. The study by O. Skvortsov & O. Mikosianchyk (2023) considered the wear resistance of electric arc coatings under the action of abrasive wear. The researchers investigated the effect of coating technology and microstructure on the development of microcracks and material loss during abrasive wear tests. The results showed that coatings with a more uniform carbide phase show better wear resistance and less tendency to crack, highlighting the importance of controlling the microstructure during surfacing.

Despite a significant number of scientific papers devoted to wear-resistant surfacing, the issue of a comprehensive assessment of the influence of the microstructure, technological modes, and mechanical characteristics of the deposited layers on the operational reliability of the blast furnace skip lining remains insufficiently covered. In particular, it is necessary to clarify the relationship between the structure of the deposited layers, hardness indicators, impact strength, and the intensity of abrasive wear under conditions close to real operation. The purpose of this study was to comprehensively assess the influence of technological parameters of surfacing and structural features of deposited wear-resistant layers on the mechanical characteristics and operational reliability of the blast furnace skip lining.

Materials and Methods

The object of the study was deposited wear-resistant layers formed on a steel base, used for the manufacture and restoration of blast furnace skip linings. As a base material, low-alloy structural steel of the VELTEK brand was used, characterised by satisfactory weldability, stable structure, and wide application in metallurgical equipment operating under abrasive and impact loads (Pokhmurska *et al.*, 2017). The samples were welded using the arc method in a protective gas environment with semi-automatic direct current welding equipment. The chosen surfacing method ensured arc stability, heat investment control, and the development of a dense deposited structure that met advanced requirements for the restoration of wear-resistant parts for metallurgical purposes (Belik *et al.*, 2016).

To conduct experimental studies, low-alloy structural steel was used as the base material, which was typical for the lining elements of metallurgical equipment in terms of chemical composition, mechanical properties, and weldability. The choice of this material was conditioned by its wide application in blast furnace shops, and the possibility of forming deposited layers without the development of technological defects, which ensured correct modelling of real operating conditions of the skip lining. The samples were made in the form of rectangular plates measuring 100 × 50 mm with a base metal thickness of 10-15 mm, which provided sufficient rigidity during surfacing and geometry stability during subsequent mechanical tests. Before surfacing, the surface of the samples was subjected to mechanical cleaning and degreasing to minimise the influence of foreign factors on the development of the deposited layer. The actual surfacing modes were selected considering the technological recommendations for arc surfacing of wear-resistant materials and the need to reduce residual stresses. Surfacing was performed at a welding current of 220-260 A and an arc voltage of 24-28 V. The speed of movement of the burner was 18-22 cm/min, which ensured the development of a uniform roller without undercuts and pores. The inter-pass temperature was maintained at a level not exceeding 150°C to limit heat accumulation and reduce the risk of thermal cracks (Zong *et al.*, 2019).

The choice of these welding modes was based on the critical influence of linear thermal energy on the development of the microstructure of the deposited layer. Microstructural studies of deposited layers and thermal impact zones were performed by optical metallography methods. Preparation of metallographic grinds was carried out according to the standard method with mechanical grinding and polishing, after which chemical etching was performed to identify the phase structure. Microstructure analysis was aimed at evaluating the morphology of reinforcing phases, the nature of their distribution, and the relationship with possible crack propagation paths (Ivanov, 2020). The hardness of the deposited layers was determined by indentation with measurement in the deposited metal, the thermal impact zone, and the base metal. This approach allowed estimating the gradient of mechanical properties in a bimetallic system, which is an important factor in the crack resistance of deposited coatings (DSTU EN 14700:2008, 2008). Wear resistance was evaluated by laboratory tests for abrasive wear, which simulate the operating conditions of the lining of a blast furnace skip. The test method corresponded to generally accepted approaches to the analysis of deposited wear-resistant materials and allowed comparing the wear intensity of different deposited layers under the same load conditions (Czupryński *et al.*, 2022).

To ensure the reliability of the results, all mechanical tests were performed on at least three samples for each series. The results were presented as average values with an indication of the root-mean-square deviation (M ± SD), which allowed estimating the spread of experimental data and ensured the correctness of the comparative analysis of the obtained characteristics (Venkatesh *et al.*, 2015). To ensure statistical reliability of the results, the study was carried out on a series of samples formed under the same technological conditions of surfacing. The total sample size was at least 24 samples, which were divided into two experimental groups depending on the structural organisation of the deposited layers. Within each group, 12 samples were made, which allowed evaluating the reproducibility of the results and reducing the impact of random errors. For each type of deposited coating, at least three parallel measurements of hardness, impact strength, and abrasive wear indicators were used, followed by the determination of average values. This approach ensured sufficient statistical reliability of experimental data and allowed correctly comparing the results obtained with each other, and with the data given in the scientific literature.

Results and Discussion

Research results have shown that the operational reliability of blast furnace skip linings is determined by a combination of intense abrasive and impact wear and a complex stress-strain state that arises during equipment operation. Analysis of the design features of the lining shown in Figure 1 shows that the most loaded areas are direct contact with abrasive material, where a combined wear mechanism is implemented.

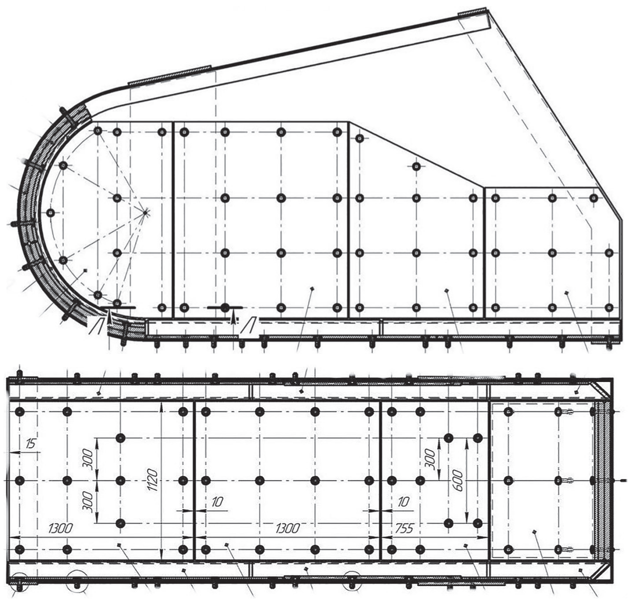

Figure 1. Drawings of the skip lining for the blast furnace

Source: created by the author

Experimentally determined values of hardness and impact strength of deposited layers are summarised in Table 1. The presented data were obtained as part of the author's experimental studies on a series of samples manufactured under the same technological conditions. Analysis of the results showed that with an increase in the hardness of the deposited layer, a decrease in impact strength is observed, which indicates an increase in the susceptibility of the material to brittle fracture. A similar relationship between hardness and impact strength is typical for wear-resistant deposited coatings and was noted by B. Venkatesh *et al*. (2015). The results of abrasive wear tests and crack resistance assessments are shown in Table 2.

Table 1. Hardness and impact strength of deposited layers of different types of materials

Brand	Hardness, HRC	Impact strength, J/cm^2	Notes
VELTEK	58	22	Optimal combination
Duroxite	55	18	High hardness, lower viscosity
SAS Global	52	20	Average indicators

Source: compiled by the author

Table 2. Abrasive wear and resistance to microcracks of modern deposited layers

Brand	Weight loss, g	Number of cracks per 100 cm^2	Notes
VELTEK	0.12	1	Best wear resistance
Duroxite	0.18	3	Moderate wear, high hardness
SAS Global	0.20	4	Largest number of cracks

Source: compiled by the author

All values were obtained in the course of experimental studies, which allows considering them as a reliable basis for analysing the operational behaviour of deposited layers. It is established that an increase in abrasive wear resistance is accompanied by a decrease in weight loss of material, but excessive rigidity of the structure increases the risk of local micro-destruction. Similar patterns were described by C. Fan *et al*. (2006), who emphasised the need for a comprehensive assessment of wear resistance and fracture resistance. Microstructural analysis of the deposited layers makes established a relationship between the phase composition and the mechanisms of crack development. Figure 2a shows the structure of a hypereutectic Fe-Cr-C alloy with a carbide phase of the M7C3 type, while Figure 2b illustrates the nature of crack propagation after microindentation. The results show that cracks are initiated mainly in the carbide phase and propagate along the interfacial boundaries, which is conditioned by the high brittleness of carbides. A similar mechanism of crack development was described in detail in the paper by R. Zahiri *et al*. (2014).

a

b

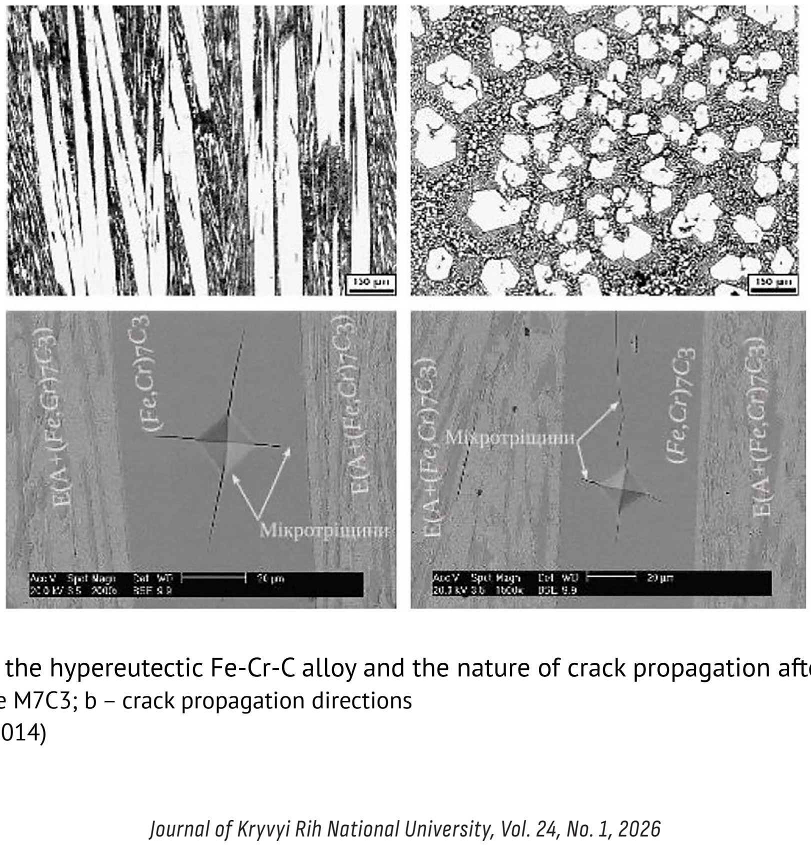

Figure 2. Structure of the hypereutectic Fe-Cr-C alloy and the nature of crack propagation after micro-indentation
Notes: a – carbide phase M7C3; b – crack propagation directions
Source: R. Zahiri *et a*l. (2014)

Comparison of microstructural observations with the mechanical characteristics given in Table 1 and Table 2 established that a more uniform distribution of the carbide phase helps to reduce the stress concentration and slow down the development of cracks. The results obtained indicate that the deposited layers are characterised by a combination of high hardness, sufficient impact strength, and increased resistance to abrasive wear, which is crucial for the operation of the blast furnace skip lining under abrasive and impact loads. The generalised mechanical characteristics of the deposited layers are shown in Table 1, and the results of tests for abrasive abrasion and crack resistance are shown in Table 2. As the analysis of the results shows, the increase in performance characteristics is conditioned by the development of a heterogeneous microstructure consisting of a metal matrix and solid carbide-type phases. Similar patterns were established by P.M. Prysyazhnyuk *et al*. (2022), who noted that the uniform distribution of carbide inclusions in the iron-containing matrix significantly increases the resistance to abrasive and erosion wear. The results obtained in this paper confirm this thesis, since samples with a more uniform structure show a lower intensity of weight wear.

The microstructural features of the deposited layers are confirmed by analysing the structure of the hypereutectic Fe-Cr-C alloy. As shown in Figure 2, the M7C3-type carbide phase forms a branched grid that effectively prevents local plastic deformation. C. Fan *et al*. (2006) noted that it is this morphology of carbides that contributes to an increase in the resistance to nucleation and propagation of microcracks under contact loading. The nature of crack development observed in this paper after microindentation is consistent with the above provisions. In the paper by L.F. Holovko *et al*. (2012), the use of laser-plasma surfacing for the development of wear-resistant surfaces of machine parts was considered. The researchers investigated a combined process in which the plasma supplies and heats the powder material, and the laser melts it together with the base, which increases the efficiency of surfacing and reduces energy costs. The main attention was paid to modelling temperature fields and selecting optimal process modes, and the conclusions showed that this approach is promising for obtaining high-quality wear-resistant coatings and reducing the volume of experimental studies. An important aspect is the ratio of hardness and impact strength of the deposited layers. According to the results presented in Table 1, an increase in hardness is not accompanied by a critical decrease in impact strength, which is fundamental for parts operating under variable impact loads. A similar effect was described by P.M. Prysyazhniuk (2024), proving that multilayer deposited coatings with an optimised structure exhibit more balanced mechanical properties compared to single-layer coatings.

The abrasive wear of the deposited layers (Table 2) decreases with increasing volume fraction of solid phases and increasing the microhardness of the matrix. B. Maroli *et al*. (2017) showed that in the case of iron-containing deposited alloys with high carbide content, wear occurs mainly by a micro-cutting mechanism, but the wear rate is significantly reduced by blocking the movement of abrasive particles. The results obtained in this paper correspond to this concept. The paper by Z.-H. Wang *et al*. (2014) investigated the microstructure and wear resistance of Fe-Cr-B-C hard-surfaced alloys produced by arc surfacing with a wire structure with flux to improve the abrasive wear resistance of the surface layers of parts. Using optical, scanning electron microscopy, and X-ray diffraction, they analysed the effect of boron content on phase development, size, and distribution of borides in the alloy, finding that as boron increases, the boride structure changes from a discontinuous to a continuous network, and at concentrations above ~3% by weight, the proportion of primary (Fe, Cr) B increases, and the distribution becomes more uniform. This leads to an increase in the hardness and abrasive wear resistance of alloys to a certain level of boron (<4%). The results showed that the controlled application of boron can significantly affect the microstructure and wear resistance of Fe-Cr-B-C deposited layers, making them promising for use under heavy friction and abrasion conditions.

Special attention should be paid to the effect of residual stresses formed during surfacing. L. Zong *et al*. (2019) emphasised that excessive structural rigidity without sufficient stress relaxation can contribute to brittle fracture. No signs of intense intergranular crack development were found in the studied samples, which indicates an acceptable level of thermal stresses formed during the surfacing process. B. Trembach *et al*. (2022) emphasised that the introduction of boron and chromium into iron-containing deposited alloys can significantly increase abrasive wear resistance without dramatically reducing ductility. The wear values obtained in this paper confirmed the feasibility of using such compositions to restore lining elements that are experiencing intense wear. The design features of the skip lining shown in Figure 1 substantiate the localisation of areas of increased abrasive and impact load. It is these zones that are critical from the standpoint of part loss, which is consistent with the conclusions of F. Franěk *et al*. (2009), who noted that the wear resistance of deposited layers should be evaluated considering actual contact conditions and element geometry. Thus, the results of experimental studies confirm the global trends established in the recent studies by foreign researchers regarding the effectiveness of the use of iron-containing deposited coatings to increase the service life of parts working in conditions of abrasive and impact wear. However, the obtained data complement the existing understanding of the relationship between the microstructure, hardness, impact strength, and mechanisms of destruction of deposited layers.

Conclusions

The paper examined the features of the development and operational behaviour of deposited wear-resistant layers designed to increase the reliability of the blast furnace skip lining. It was shown that the nature of lining wear is determined by a combination of abrasive and impact load and a complex stress-strain state formed in the most loaded zones of the structure. It was established that the mechanical and operational properties of deposited layers significantly depend on their microstructural organisation. The development of structures with a high content of the carbide phase contributes to an increase in hardness and abrasive wear resistance, but is accompanied by an increase in the tendency to brittle fracture. It was found that the uneven distribution of carbide inclusions is one of the main factors for the initiation and development of cracks in the deposited layers. The use of multilayer deposited systems helps to reduce hardness gradients and stress redistribution in the thermal impact zone, which positively affects the resistance to destruction of deposited coatings. The results obtained confirm the feasibility of a comprehensive approach to choosing the structure of deposited layers, which takes into consideration not only the hardness and wear resistance indicators, but also the ability of the material to counteract crack development under operating conditions. The results of the study are consistent with the situation as of 2025 and can be used to substantiate technological solutions for the restoration of blast furnace skip linings in order to extend their service life and improve operational reliability. A promising area of further research is an in-depth microstructural analysis of deposited layers and thermal impact zones using quantitative phase analysis to establish the relationship between the morphology of reinforcing phases and fracture resistance indicators. It is advisable to use methods of numerical modelling of the stress-strain state to assess the effect of residual and thermal stresses on the development of cracks in multilayer systems. Special attention should be paid to the study of the effect of heat treatment after surfacing on reducing the level of residual stresses and stabilising the microstructure of the deposited layers. Further research in this area will expand the practical application of the developed technological solutions and increase the efficiency of restoring blast furnace equipment elements.

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Conflict of Interest

None.

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Підвищення тріщиностійкості футерівки скіпа доменного цеху

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Анотація. Експлуатація футірки скипа доменного цеху супроводжується інтенсивним абразивно-ударним зношуванням, через що актуально розробляти залізовмісні наплавні матеріали з гетерогенною карбідною мікроструктурою для підвищення міцності та зносостійкості. Метою роботи було підвищення механічної міцності та довговічності футірки скипа доменного цеху шляхом оптимізації структури наплавлених шарів і встановлення закономірностей між мікроструктурою, механічними властивостями та зносостійкістю покриттів. Дослідження виконано з використанням електродугового наплавлення на зразках зі сталі 09Г2С. Проведено випробування на твердість, ударну в'язкість і абразивне стирання, а також мікроструктурний аналіз наплавлених шарів і оцінку характеру тріщиноутворення після мікроіндентування. Основні результати експериментальних досліджень показують, що твердість наплавлених шарів коливалася від 52 HRC у матеріалу SAS Global до 58 HRC у ВЕЛТЕК, тоді як ударна в'язкість змінювалася від 18 Дж/см² у Duroxite до Дж/см² у ВЕЛТЕК, що демонструє обернену залежність між твердостю та ударною в'язкістю: більш тверді шари мають більшу схильність до крихкого руйнування. У випробуваннях на абразивне стирання встановлено, що ВЕЛТЕК проявив найкращу зносостійкість із масовою втратою 0,12 г та лише однією тріщиною на 100 см², тоді як SAS Global характеризувався найбільшою кількістю тріщин (4 на 100 см²) і втратою маси 0,20 г, а Duroxite мав проміжні значення – 0,18 г втрати маси та 3 тріщини. У результаті встановлено, що формування заевтектичної структури з карбідною фазою типу M_7C_3 сприяє зниженню інтенсивності абразивного зношування та обмеженню поширення мікротріщин. Отримані наплавлені шари характеризуються поєднанням підвищеної твердості та достатньої ударної в'язкості, що є критичним для роботи футірки в умовах змінних ударних навантажень. Практична цінність результатів полягає у можливості їх використання при відновленні та модернізації футірки скипів доменних печей з метою збільшення міжремонтного ресурсу та зниження експлуатаційних витрат

Ключові слова: наплавлення; мікроструктура; зношування; міцність; залишкові-напруження; твердість