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СТРУКТУРОУТВОРЕННЯ. ОПІР РУЙНУВАННЮ ТА ФІЗИКО-МЕХАНІЧНІ ВЛАСТИВОСТІ

STRUCTURE FORMATION. RESISTANCE TO DESTRUCTION AND PHYSICAL-MECHANICAL PROPERTIES

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Gennadii Snizhnoi	Doctor of Technical Sciences, Professor, Professor of the Department of Information Security and Nanoelectronics, National University Zaporizhzhia Polytechnic, Zaporizhzhia, Ukraine, *e-mail: snow@zp.edu.ua*, ORCID: 0000-0003-1452-0544
Volodymyr Sazhnev	Candidate of Technical Sciences, Associate Professor of the Department of Machines and Foundry Technology, National University Zaporizhzhia Polytechnic, Zaporizhzhia, Ukraine, *e-mail: sajhnev@zp.edu.ua*, ORCID: 0000-0002-2095-4958
Leonid Cherepyns’ky	Candidate of Technical Sciences, Senior Research of the Department of Machines and Foundry Technology, National University Zaporizhzhia Polytechnic, Zaporizhzhia, Ukraine, *e-mail: leonid.cherepinskiy@gmail.com*, ORCID: 0009-0004-3642-0573
Kristina Snizhna	Student of the Faculty of Construction, Architecture and Design, National University Zaporizhzhia Polytechnic, Zaporizhzhia, Ukraine, *e-mail: snowshade66@gmail.com*, ORCID: 0009-0005-1230-0283

SELECTION OF MODIFIERS FOR HIGH-MANGANESE STEEL DEPENDING ON THE OPERATING CONDITIONS OF MINING AND PROCESSING EQUIPMENT COMPONENTS

Purpose. *To establish the optimal modifier for increasing the strength and ductility properties of high-manganese Hadfield steel, as well as wear resistance during dry and wet grinding in an alkaline environment.*

Research methods. *Impact and abrasive wear resistance tests during wet and dry grinding were carried out in a ball mill. Tensile tests were carried out on a URM-50 machine. Determination of the impact strength of samples with a U-shaped notch was carried out on a pendulum impactor MK-30A according to DSTU ISO 148-1:2022. Brinell hardness was determined according to DSTU ISO 6506-1:2007.*

Results. *Based on the results of experimental studies, it was found that the optimal way to increase the physical and mechanical properties and wear resistance of high-manganese steel during dry grinding is a complex modification with titanium and vanadium with preliminary deoxidation with aluminum. The optimal technological factor that increases the wear resistance of high-manganese steel parts during wet grinding in an alkaline environment is the modification of the melt with 0.05 ... 0.15% Nb with preliminary deoxidation with aluminum.*

Scientific novelty. *In steel modified with aluminum, film nitrides of aluminum were found, around which, apparently, corrosion destruction occurs. When modifying Nb within 0.06–0.12 %, film nitrides are practically absent. The bulk of the inclusions were complex nitrides of aluminum and niobium, as well as carbonitrides of niobium. The effect of niobium on wear resistance is positive and during wet grinding has a pronounced extreme character with an optimum at a content of 0.12% Nb.*

Practical value. *An optimal method for improving the physical and mechanical properties and wear resistance of high-manganese steel during dry grinding has been identified: complex modification with titanium and vanadium followed by aluminum deoxidation. The optimal process factor for increasing the wear resistance of high-manganese steel components during wet grinding in an alkaline environment is niobium modification of the melt. The proposed recommendations will reduce the material intensity of mining and processing equipment, improve production, and increase the reliability and durability of high-manganese steel components.*

Key words: *Hadfield steel, modification, boron, niobium, impact toughness, wear resistance, alkaline environment.*

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Introduction

The main range of castings made of wear-resistant high-manganese steel at mining and processing enterprises consists of quickly wearing replaceable parts for crushing and grinding equipment (Fig. 1) and excavators (Fig. 2). The working parts of this equipment include crushing plates, cones, bowls, hammers, sidewalls of the crusher working zones, the main structural elements of the mill drums, which form the grinding chamber surfaces, front walls, bucket teeth, rocker arms, bottom hinges, and links. These components come into contact with the material being ground or the pulp during operation. To ensure structural strength and reliability, they are entirely manufactured or lined with Hadfield steel (110G13L).

During operation, the above-mentioned parts are subjected to tensile, compressive, bending, shear loads, and are subjected to abrasive wear. It is possible to combine two or more types of destructive action on the same part.

The armor of jaw and cone crushers during operation is subjected to very high loads and wears out to a considerable depth, and in some places even the entire thickness of the part. The presence in the castings of even minor casting defects, unsatisfactory structure or low values of the mechanical properties of the steel under such loads leads to premature failure of the armor due to cracks (Fig. 3).

Mill liners operating under very low impact loads are primarily subject to abrasive wear (Fig. 4*a*).

The front wall and teeth of an excavator bucket are subject to abrasive wear under significant impact loads. Due to the rigid shape of these components, they are highly susceptible to work hardening and therefore resist impacts well. The abrasive wear of the front wall and teeth of an excavator bucket is similar (Fig. 4*b*).

a *b*

Figure 1. Details of crushing and grinding equipment made of 110G13L steel:
a – cone crusher armor; *b* – ball mill lining

a *b*

Figure 2. Excavator parts made of 110G13L steel:
a – front wall of the excavator bucket; *b* – excavator bucket tooth

a *b*

Figure 3. Parts of a cone crusher made of 110G13L steel that have failed:
a – worn out armor of the cone crusher; *b* – crack in the armor of the cone crusher

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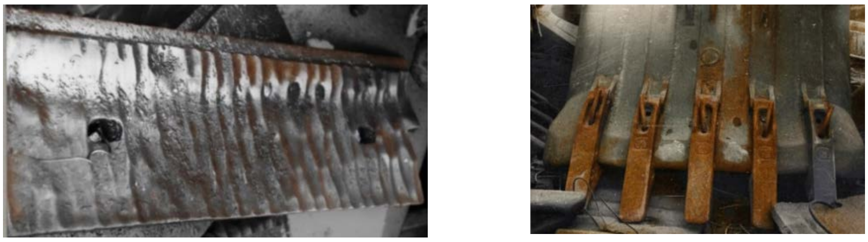
a *b*

Figure 4. Worn parts of a ball mill and an excavator made of 110G13L steel:
a – worn lining of the ball mill drum; *b* – worn front wall of an excavator bucket with teeth

Thus, abrasive wear of replaceable parts in mining and processing equipment is the predominant factor causing failure during operation. However, abrasive wear occurs under various operating conditions, including both parts operating without significant impacts and pressures, and parts subject to strong impacts and high pressures. Abrasive wear without impacts and pressures requires high-hardness steel, while impact wear requires high-impact steel.

Analysis of research and publications

To ensure a reduction in the material consumption of mining and processing equipment, improve production, increase its reliability and durability, researchers are constantly proposing various technological measures to increase the stability of mining and processing equipment parts. Improving the operational properties of high-manganese steel is achieved by optimizing the chemical composition of steels for specific groups of castings, heat treatment, modification [1–4].

A significant part of the research aimed at reducing the wear of high-manganese steels is associated with changing the dispersion of the crystallizing phases by introducing small additives of individual elements, compounds into the liquid steel, i.e. modification. The most widespread modifiers are titanium, vanadium, cerium, calcium, zirconium, niobium, tantalum, hafnium, boron [5–7].

At the same time, the effect of modification on the operational stability of high-manganese steels operating in the conditions of mining and dry grinding of ores and minerals has been studied quite fully. But in the preparatory processes for ore enrichment, for example, when grinding in ball mills, wet grinding is used. The mechanisms of wear, and accordingly the wear resistance, are different in wet and dry grinding due to the influence of the corrosive environment and differ significantly [8].

The presence of dissolved and gaseous oxygen, chlorides, sulfides, carbonates and other substances in the pulp that can enter into chemical reactions with the exposed metal surface of the mill linings significantly accelerates its destruction compared to dry grinding. And in the practice of manufacturing castings of linings, grates, “lifters”, wedges, etc., which are operated in wet grinding conditions in alkaline environments with pH 9...12, this is not given importance.

Thus, traditional technological measures aimed at increasing resistance, in wet grinding in some cases do not lead to the expected result.

The purpose of the work

The aim of this investigation is to identify optimal modifiers for high-manganese steel to improve its physical and mechanical properties and wear resistance. It also aims to develop recommendations for selecting Hadfield steel modifiers based on the operating conditions of mining and processing equipment components (pressure, alkaline environment).

Research material and methodology

Impact and abrasive wear resistance tests during wet and dry grinding were carried out in a semi-industrial ball mill. ∅ 680×700 mm at n = 34 rpm for 100 h for each type of grinding. Cast metal samples (9×9×25 mm) were used for the tests. Tensile tests were carried out on a URM-50 machine. To determine the impact strength, samples with a U-shaped notch were tested on a pendulum impactor MK-30A according to DSTU ISO 148-1:2022. Brinell hardness was determined according to DSTU ISO 6506-1:2007. Relative wear resistance was determined as the ratio of the sample's mass loss to the standard's mass loss. The standard was Hadfield steel (1.1C-13Mn), deoxidized with 0.04 wt.% aluminum and containing no other modifiers. In dry grinding, 50 kg of nepheline ore and 14 balls ∅ 100 mm were loaded into the mill. The ore was replaced every 10 hours. In wet grinding, the test was carried out similarly. An aqueous solution of sodium and potassium carbonates (pH 12) was used as a corrosive medium. The pulp was replaced every 10 hours.

Impact research of the influence of traditional modifiers: calcium, rare earth metals (REM), titanium, vanadium were performed at their optimal concentrations, confirmed by many studies [9, 10]. Studies of the influence of boron and niobium, which are used to modify high-manganese steels less often, and data on optimal additives and their influence on the complex of properties are contradictory, were carried out at several different concentrations of modifiers. For the tests, Hadfield steel (1.1C-13Mn or 110G13L) was melted in an induction crucible furnace IST-0.16 with a main lining using the

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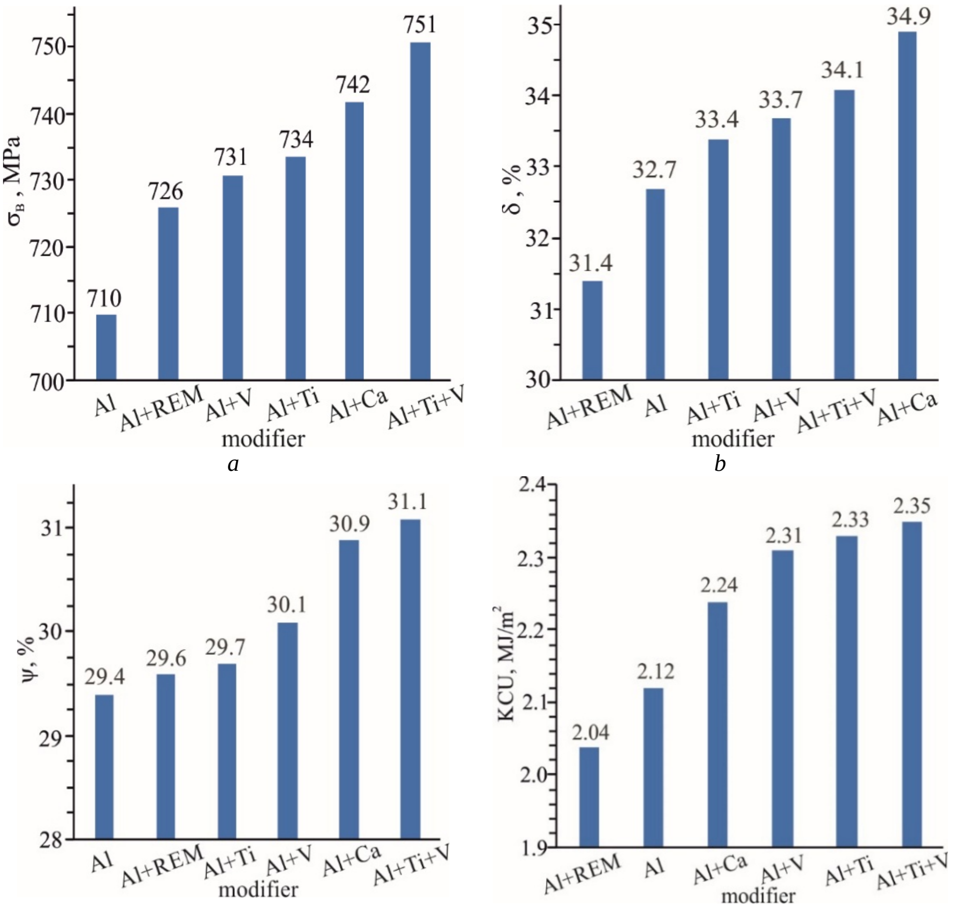
method of portioned metal selection, which eliminates the influence of extraneous factors [11]. The content of the modifier elements in the corresponding portions of steel is given in Table 1.

Table 1 – Content of modifying elements in Hadfield steel (1.1C-13Mn), wt.%.

№ melting	Al	Ti	Ca	REM	V	B	Nb
1	0.04	–	–	–	–	–	–
2	0.04	0.2	–	–	–	–	–
3	0.04	–	0.1	–	–	–	–
4	0.04	–	–	0.15	–	–	–
5	0.04	–	–	–	0.2	–	–
6	0.04	0.2	–	–	0.2	-	–
7	0.04	–	–	–	–	0.001	–
8	0.04	–	–	–	–	0.006	–
9	0.04	–	–	–	–	0.012	–
10	0.04	–	–	–	–	–	0.06
11	0.04	–	–	–	–	–	0.12
12	0.04	–	–	–	–	–	0.18
13	0.04	–	–	–	–	–	0.24

Research results

The results of tests of the influence of traditional modifiers (No. 1–6, Table 1) on the mechanical properties and relative wear resistance during wet and dry grinding of Hadfield steel are shown in Fig. 5, 6. The change in strength and plastic properties occurs in the following sequence of modifying elements: increase tensile strength $\sigma_{\text{в}}$: Al→ Al+REM→ Al+V→ Al+Ti→ Al+Ca→ Al+Ti+V (Fig. 5 a), increase relative elongation δ: Al+REM→ Al→ Al+Ti→ Al+V→ Al+Ti+V→ Al+Ca (Fig. 5*b*), increase relative narrowing ψ: Al→ Al+REM→ Al+Ti→ Al+V→ Al+Ca→ Al+Ti+V (Fig. 5 c), increase impact toughness KCU: Al+REM→ Al→ Al+Ca→ Al+V→ Al+Ti→ Al+Ti+V (Fig. 5*d*). It should be noted that the modification of Hadfield steel with Al+Ti+V and Al+Ca complexes causes the highest values of relative elongation (δ) 34.1% and 34.9%, respectively. Thus, the optimal modifier is the Al+Ti+V complex, which leads to the best result in increasing the plastic properties of Hadfield steel.



a *b*

c *d*

Figure 5. Strength and plastic properties of Hadfield steel (1.1C-13Mn) depending on the content of traditional modifiers: *a* – tensile strength $\sigma_{\text{в}}$; *b* – relative elongation δ; *c* – relative narrowing ψ; *d* – impact toughness KCU

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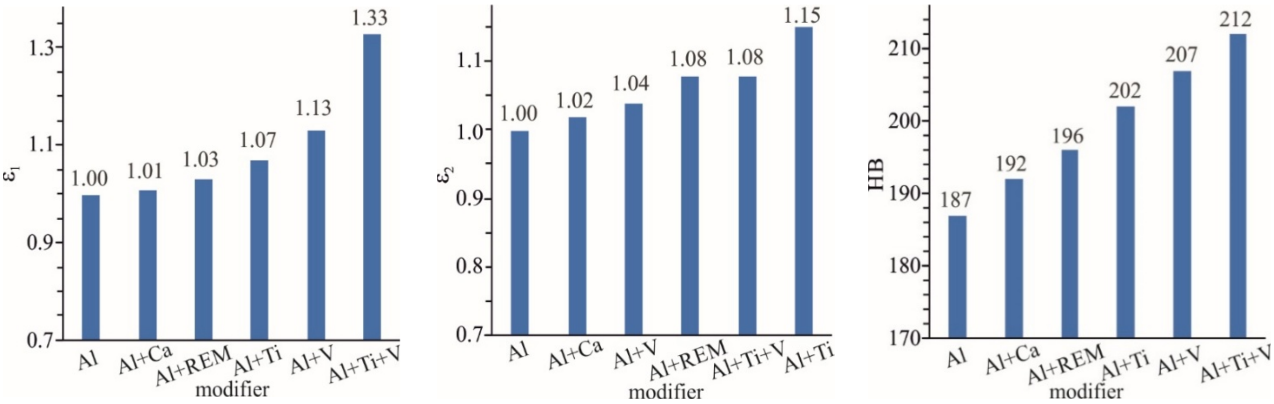

a *b* *c*

Figure 6. Wear resistance and hardness of Hadfield steel (1.1C-13Mn) depending on the content of traditional modifiers: *a* – wear resistance of dry grinding ε_1; *b* – wear resistance of wet grinding ε_2; *c* – hardness HB

The increase in wear resistance and hardness occurs in the following sequence of modifying elements: dry grinding wear resistance ε_1 : Al → Al+Ca → Al+REM→ Al+Ti → Al+V → Al+Ti+V (Fig. 6 a), increase wet grinding wear resistance ε_2: Al→ Al+Ca → Al+V →Al+REM→ Al+Ti+V → Al+Ti (Fig. 6*b*), increase HB hardness: Al→ Al+Ca → Al+REM → Al+Ti→ Al+V → Al+Ti+V (Fig. 6 c). It should be noted that the modification of Hadfield steel with the Al+Ti+V complex causes the highest values of dry grinding wear resistance ε_1 =1.33, and the modification of Al+Ti – the highest values of wet grinding wear resistance ε_2 = 1.15. Thus, depending on the operating conditions of the equipment (dry or wet grinding), it is recommended to melt parts from Hadfield steel, which contains the Al+Ti+V or Al+Ti complex.

The test results showed that the most effective increase in mechanical properties and impact-abrasive wear resistance during dry grinding was provided by titanium and compatible titanium and vanadium additives. A significant increase in mechanical properties was also obtained when modified with calcium. REM additives led to a decrease in mechanical properties, except for the tensile strength. In order to identify the role of each element, metallographic studies of samples of Hadfield steels containing various modifiers were performed (Fig. 7).

Metallographic studies of steels modified with titanium, calcium, REM and vanadium showed that the nature and form of non-metallic inclusions are directly related to the content of the modifying element. In steel deoxidized with aluminum, globular inclusions of aluminomanganese silicates were found (Fig. 7*b*). Additions of calcium and REM led to the grinding and reduction of the total number of globular inclusions (Fig. 7*c*, *d*). Modification with titanium and vanadium led to the formation of nitrides and carbonitrides (Fig. 7*e*, *f*).

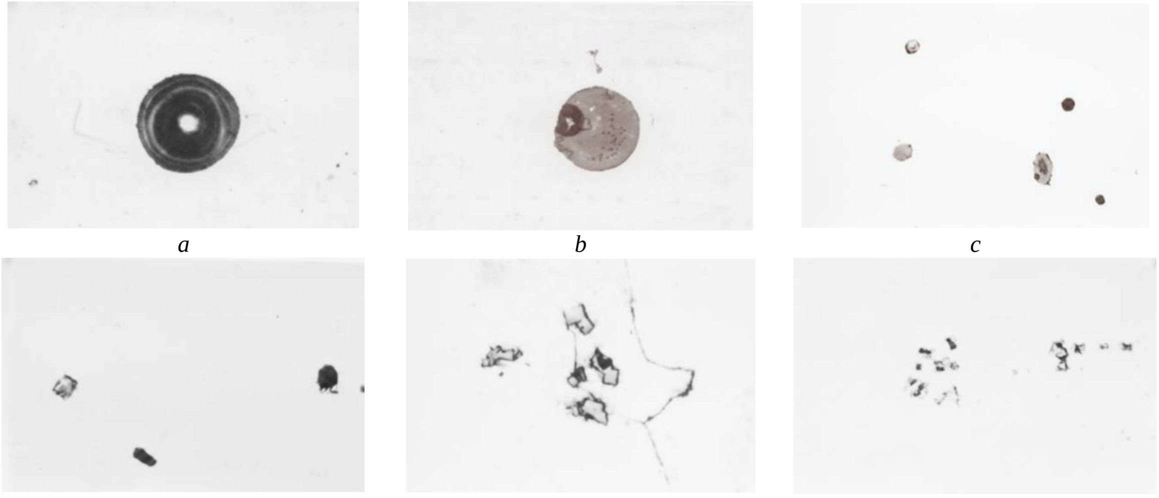
a *b* *c*
d *e* *f*

Figure 7. Non-metallic inclusions in modified steel 110G13L (× 575): *a* – manganese silicate; *b* – aluminomanganese silicate in steel deoxidized with aluminum; *c* – complex oxysulfide in steel modified with silicate calcium; *d* – complex oxides in steel with rare earth elements; *e* – titanium nitrides; *f* – vanadium carbonitrides

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Microfractographic studies have established that the properties of high-manganese steel are most influenced by finely dispersed nitride inclusions. In fractures of steel deoxidized with aluminum, film-like aluminum nitrides were found, around which a brittle fracture zone developed (Fig. 8*a*). In steel modified with titanium, the bulk of nitride inclusions consisted of titanium nitrides of regular cubic shape (Fig. 8*b*). When modified with vanadium, vanadium nitrides were found in the steel (Fig. 8*c*). When combined with titanium and vanadium modification, complex inclusions were obtained, which were identified as aluminum, titanium, and vanadium nitrides (Fig. 8*d*).

During wet grinding in an alkaline environment, the impact-abrasive wear resistance decreased sharply compared to dry grinding. The decrease in wear resistance during modification with calcium, REM and vanadium can be explained by the supersaturation of grain boundaries with harmful phases and chemical compounds that initiate corrosion destruction.

The results of tests of the influence of increasing boron and niobium additives on the mechanical properties and relative wear resistance during wet and dry grinding of Hadfield steel (1.1C-13Mn) are shown in Fig. 9 and 10.

The influence of increasing boron and niobium additives on the physical and mechanical properties of high-manganese steel is the same: the strength characteristics increased (Fig. 9*a*), and the plastic characteristics (Fig. 9*b*, *c*) and impact toughness (Fig. 9*d*) monotonically decreased. However, the effects of boron and niobium on the wear resistance of Hadfield steel are significantly different.

No noticeable effect of increasing boron additions on wear resistance was found (Fig. 10). Some decrease in wear resistance is probably due to the brittle effect of grains of eutectic carboboride structures, which are allocated along grain boundaries and which reduce the operational properties of high-manganese steel.

The effect of niobium on wear resistance is positive and during wet grinding has a pronounced extreme character with an optimum at a content of 0.12 % Nb. Further increase in the niobium content monotonically reduced wear resistance. The obtained results are in good agreement with the obtained data of microfractographic studies.

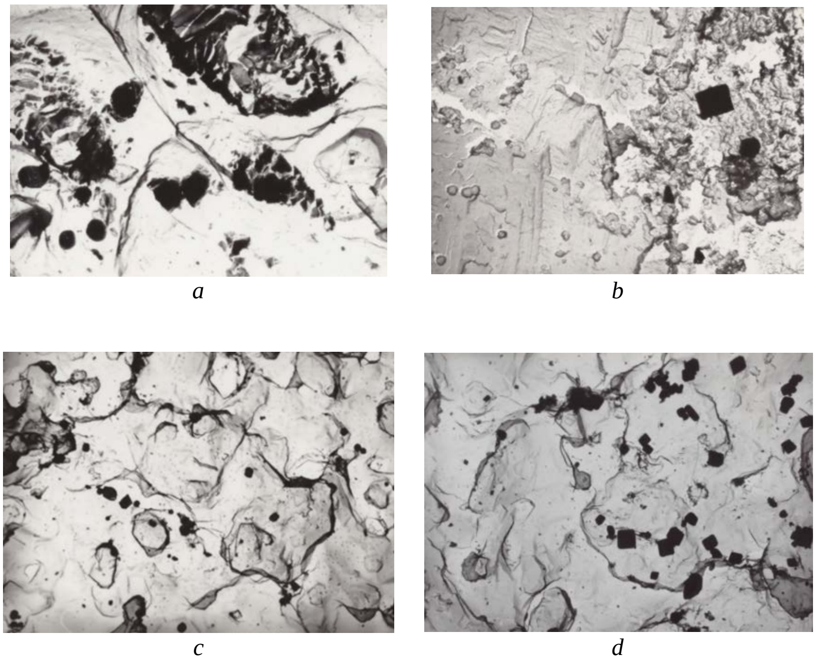
a *b*
c *d*

Figure 8. Nitride inclusions in 110G13L steel (× 10000):
a – film aluminum nitrides; *b* – titanium nitrides; *c* – vanadium nitrides; *d* – aluminum, titanium and vanadium nitrides

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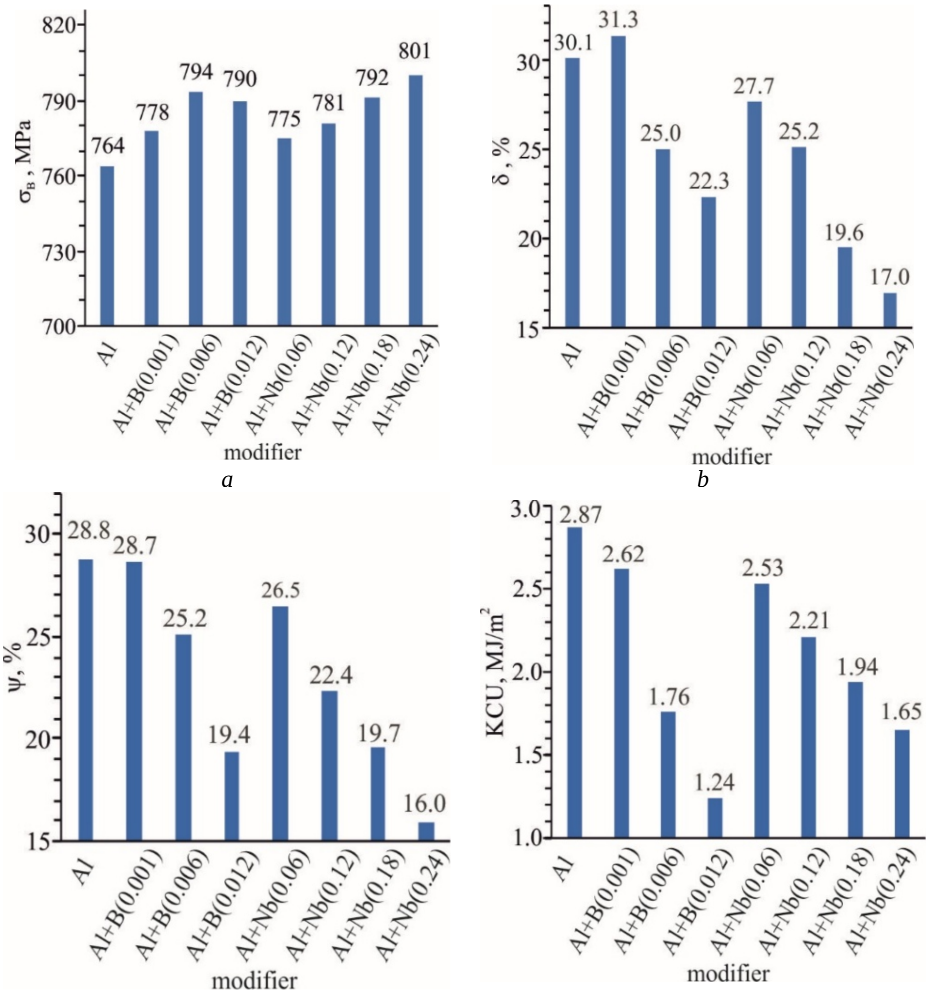
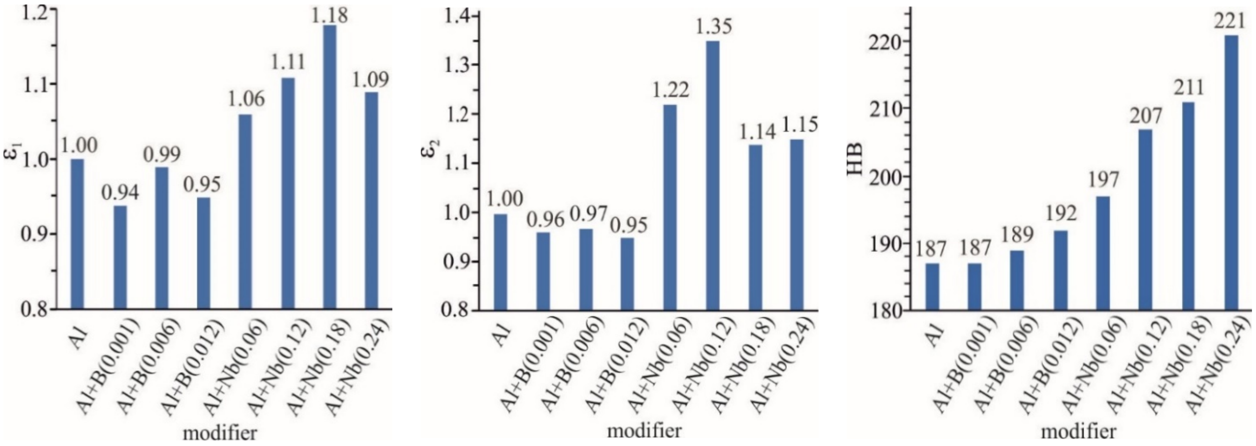


a *b*

c *d*

Figure 9. Plastic properties of Hadfield steel (1.1C-13Mn) depending on the content of increasing boron and niobium additives: a – tensile strength σ_B ; b – relative elongation δ; c – relative narrowing ψ; d – impact toughness KCU



a *b* *c*

Figure 10. Wear resistance and hardness of Hadfield steel depending on the content of increasing boron and niobium additives: *a* – wear resistance of dry grinding ε_1; *b* – wear resistance of wet grinding ε_2; *c* – hardness HB

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Discussion

In Hadfield steel modified with aluminum, film aluminum nitrides were found, around which, apparently, corrosion destruction occurs. No significant effect of boron additives on the wear resistance of 110G13L steel was observed. The effect of tempering temperature on the microstructure, mechanical properties, and wear resistance of manganese-boron steel was studied in [11]. When tempered at 150 °C, this steel exhibits the best combination of strength, impact toughness, and wear resistance. Therefore, to achieve significant results from boron modification, additional research on the heat treatment of 110G13L steel is necessary.

When modifying Nb within 0.06-0.12 %, film nitrides are practically absent. The bulk of the inclusions were complex nitrides of aluminum and niobium, as well as niobium carbonitrides. The metal had a homogeneous austenitic finely dispersed structure. Modification with niobium contributes to the conversion of film inclusions into bulk inclusions, which are released in liquid steel and act as modifiers of the second kind. The effect of phosphide eutectic is also weakened. At a niobium content > 0.18 %, the steel is contaminated with coarse complexes of niobium carbonitrides, which are released along grain boundaries and reduce wear resistance in corrosive environments.

Conclusions

1. It has been established that the optimal way to increase the physical and mechanical properties and wear resistance of high-manganese steel during dry grinding is complex modification with titanium and vanadium with preliminary deoxidation with aluminum.
2. It has been established that the optimal technological factor that increases the wear resistance of parts made of high-manganese steel during wet grinding in an alkaline environment is the modification of the melt with 0.05 ... 0.15% Nb with preliminary deoxidation with aluminum.

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ВИБІР МОДИФІКАТОРІВ ВИСОКОМАРГАНЦЕВОЇ СТАЛІ В ЗАЛЕЖНОСТІ ВІД УМОВ ЕКСПЛУАТАЦІЇ ДЕТАЛЕЙ ГІРНИЧО-ЗБАГАЧУВАЛЬНОГО ОБЛАДНАННЯ

Геннадій Сніжной — д-р техн. наук, професор, професор кафедри інформаційної безпеки та наноелектроніки, Національний університет «Запорізька політехніка», Запоріжжя, Україна, *e-mail: snow@zp.edu.ua*, ORCID: 0000-0003-1452-0544**;**

Володимир Сажнєв — канд. техн. наук, доцент, доцент кафедри машин та технології ливарного виробництва, Національний університет «Запорізька політехніка», Запоріжжя, Україна, *e-mail: sajhnev@zp.edu.ua*, ORCID: 0000-0002-2095-4958

Леонід Черепинський — канд. техн. наук, старший науковий співробітник кафедри машин та технології ливарного виробництва, Національний університет «Запорізька політехніка», Запоріжжя, Україна, *e-mail: leonid.cherepinskiy@gmail.com*, ORCID: 0009-0004-3642-0573

Крістіна Сніжна — студентка факультету будівництва, архітектури та дизайну, Національний університет «Запорізька політехніка», Запоріжжя, Україна, *e-mail: snowshade66@gmail.com*, ORCID: 0009-0005-1230-0283

Мета роботи. *Встановити оптимальний модифікатор підвищення міцнісних та пластичних властивостей високомарганцевої сталі Гадфільда, а також і зносостійкості при сухому та мокрому помелі в лужному середовищі.*

Методи дослідження. *Випробування на ударно-абразивну зносостійкість при мокрому і сухому помелі проводили в кульовому млині. Випробування на розрив проводили на машині УРМ-50. Визначення ударної в'язкості зразків з U-подібним надрізом проводили на маятниковому копрі МК-30А згідно ДСТУ ISO 148-1:2022. Твердість за Брінеллем визначали згідно ДСТУ ISO 6506-1:2007.*

Отримані результати. *Виходячи з результатів експериментальних досліджень, встановлено, що оптимальним способом підвищення фізико-механічних властивостей і зносостійкості високомарганцевої сталі при сухому подрібненні є комплексне модифікування титаном і ванадієм з попереднім розкисленням алюмінієм. Оптимальним технологічним фактором, який підвищує зносостійкість деталей з високомарганцевої сталі при мокрому помелі в лужному середовищі, є модифікування розплаву 0.05 ... 0.15% Nb з попереднім розкисленням алюмінієм.*

Наукова новизна. *У сталі, модифікованої алюмінієм, виявлено плівкові нітриди алюмінію, навколо яких, очевидно, відбувається корозійна руйнація. При модифікуванні Nb у межах 0.06–0.12% плівкові нітриди практично відсутні. Основну масу включень склали комплексні нітриди алюмінію та ніобію, а також карбонітриди ніобію. Вплив ніобію на зносостійкість позитивно і при мокрому помелі має яскраво виражений екстремальний характер з оптимумом при вмісті 0.12 % Nb.*

Практична цінність. *Визначено оптимальний спосіб підвищення фізико-механічних властивостей та зносостійкості високомарганцевої сталі при сухому подрібненні, а саме комплексна модифікація титаном та ванадієм з попереднім розкисленням алюмінієм.Оптимальним технологічним фактором, що підвищує зносостійкість деталей високомарганцевої сталі при мокрому помелі в лужному середовищі, є модифікація розплаву ніобієм. Запропоновані рекомендації дозволять знизити матеріаломісткість гірничо-збагачувального обладнання, удосконалити виробництво, підвищити надійність та довговічність деталей із високомарганцевої сталі.*

Ключові слова: *сталь Гадфільда, модифікація, бор, ніобій, ударна в'язкість, зносостійкість, лужне середовище.*

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