UDC 537.621.4:620.17:53.082.7

Vadym Ol'shanetskii — Dr. Sc., Professor, Professor of the Department of Physical Materials Science, National University Zaporizhzhia Polytechnic, Zaporizhzhia, Ukraine, *e-mail: olshan@zp.edu.ua*, ORCID: 0000-0002-9485-4896

Gennadii Snizhnoi — Dr. Sc., 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 — Ph. D, Associate professor, Associate Professor of the Department of Machines and Foundry Technology, National University Zaporizhzhia Polytechnic, Zaporizhzhia, *e-mail: sajhnev@zp.edu.ua*, ORCID: 0000-0002-2095-4958

Olga Vasylenko — Ph. D, Associate professor, Associate professor of the Department of Information Security and Nanoelectronics, National University Zaporizhzhia Polytechnic, Zaporizhzhia, Ukraine, *e-mail: drvasylenkoolga@gmail.com*, ORCID: 0000-0001-6535-3462

Denys Onyshchenko — Postgraduate student A-132, National University Zaporizhzhia Polytechnic, Zaporizhzhia, Ukraine, *e-mail: denys.onyshchenko@zp.edu.ua*, ORCID: 0009-0008-4766-7052

QUALITY CONTROL OF HIGH-MANGANESE STEELS BY THE PARAMAGNETIC STATE OF AUSTENITE

Purpose. *Determination of the methodology for the comprehensive evaluation of the mechanical properties of high-manganese steels according to one parameter that is sensitive to the influence of external factors, which will contribute to the reduction of laboratory research costs during the selection of the best samples (melts) of steel for the production of quality-critical products of responsible mechanical engineering.*

Research methods. *Tearing tests were carried out on the УРМ-50 machine, the relative elongation was determined according to the standard method. Microhardness was measured using a ПМТ3 device at a load of 50 g by a standard method. Determination of the specific paramagnetic susceptibility* χ_0 *of austenite (before mechanical tests) was carried out on automated magnetometric scales.*

Results. *Based on the results of experimental studies, a correlation between mechanical properties and specific paramagnetic susceptibility* χ_0 *of austenite was established. The parameter* χ_0 *is a characteristic of the atomic-magnetic state of austenite and is a supersensitive value to the influence of various external factors. That is why it is proposed to use the specific paramagnetic susceptibility of austenite as an integral characteristic to determine the influence of various factors (chemical composition, smelting conditions, deformation, temperature, etc.) on the properties of steel.*

Scientific novelty. *The idea of a relationship between the mechanical properties of austenitic steels and the previously formed atomic-magnetic state of the austenite matrix was proposed and experimentally confirmed.*

Practical value. *The determined correlation between the mechanical properties of high-manganese steels and the specific paramagnetic susceptibility* χ_0 *of austenite and the proposed trend correspondence matrix make it possible to perform express forecasting and quality control of steels without conducting labor-intensive mechanical tests.*

Key words: *austenite, elongation, durability, deformation martensite, paramagnetic susceptibility.*

Introduction

The combination of physical, chemical and technological properties affect the quality of steels and products made from them. Depending on the available properties, the fields of application and the corresponding grade or classification are determined. The future properties of steel are largely determined by the final chemical composition, phase-structural composition, and processing methods (heat treatment, mechanical, etc.).

Two approaches are used to evaluate the quality of steel. In the first case, a specific mechanical (hardness, impact strength, wear resistance, tensile strength, etc.) or service (for example, corrosion rate) parameter is experimentally determined, which is then brought into line with a specific DSTU or technical task (customer requirements). Measurement and analysis of each of these parameters requires significant time, qualified personnel, specific equipment, etc. For example, the manufacture of samples to determine mechanical properties is a rather laborious process, and corrosion tests can last several weeks.

These experimental studies are reflected in the standards of enterprises with input (output) control of materials (products), that is, they are mandatory at the initial and final stages of production. Intermediate tests are generally not conducted due to their time-consuming and expensive nature.

The second approach is to define and use one physical parameter, which would be an integral characteristic of the

DOI 10.15588/1607-6885-2025-1-3

influence of various factors (chemical composition, smelting conditions, the influence of deformation and temperature, etc.). A necessary condition for its use is a certain relationship (correlation) of this parameter with the mechanical and service properties that determine the quality of steel.

Qualitative and timely control of the physical and mechanical properties of substances contributes to increasing the competitiveness of machine-building enterprises.

Research and publication analysis

High-manganese steels are widely used for the manufacture of a significant range of parts for mining and processing equipment and railway transport [1-4]. The continuous development of these industries leads to a complication of the operating conditions of parts and an increase in the requirements for the physical and mechanical properties of steels.

During the operation of products, phase-structural transformations occur, for example, martensitic $\gamma \rightarrow \alpha'$ transformation during plastic deformation [5, 6].

The martensitic transformation in austenitic high-manganese steels is significantly influenced by the chemical composition, microstructure, deformation temperature, and mechanical stress [7].

In [8], an algorithm for performing material quality evaluation is presented, according to which the test method is selected and the necessary qualimetric methods for quality evaluation are selected.

A highly accurate indicator of structural changes and mechanical properties is the paramagnetic susceptibility χ_0 of austenite, which, as a highly sensitive characteristic, is able to reflect the peculiarities of the influence of temperature, pressure and chemical composition (i.e., the content of Mn, C, Si and other elements) on the general state and properties of the austenite phase [9].

Since the main phase of austenitic high-manganese steels is austenite, it is quite natural to consider one of the characteristics of austenite. A common means of studying austenitic materials is to consider the lattice, grain shape, defects, and alloying elements. However, each of these parameters is not integrated, that is, it does not reflect all the components of the formed austenite matrix. The atomic-magnetic state of austenite is characterized by the specific paramagnetic susceptibility χ_0, which is determined by the total magnetic moment of a unit mass of austenite under the condition of a unit value of the magnetic field.

While, the parameter χ_0 is a complex characteristic of austenite, the state of which was formed due to the available chemical elements, mechanical and temperature effects, that is, χ_0 is sensitive to external factors [10].

Research objective

The purpose of the study is the development of a methodology for comprehensive evaluation of the mechanical properties of high-manganese steels by determining the specific paramagnetic susceptibility χ_0 of austenite. The parameter χ_0 is a characteristic of the atomic-magnetic state of the austenite matrix.

Materials and research methods

High-manganese steels with different manganese contents were obtained in induction crucible electric furnaces in the form of ingots 100×100×200 mm, and then subjected to water quenching from 1050 °C for austenization (3 h holding time).

The content of other elements was kept within the limits of the chemical composition for steel 110G13L according to the DSTU 8781:2018 standard.

The chemical composition of the studied steel melting samples is given in Table 1. The studied samples are numbered, which facilitated the construction of characteristics in the figures presented later in the text. The values of the measured parameter are rounded to the third decimal place.

Table 1 – Chemical composition of the studied austenitic steels

Steel melting sample №	Steel grade	Element, % of mass						
		C	Mn	Si	S	P	Cr	Al
1	110Г8Л	1.14	8.60	0.66	0.040	0.088	0.100	0.019
2	110Г10Л	1.30	10.70	0.87	0.014	0.084	0.100	0.021
3	110Г13Л	1.16	13.80	0.76	0.016	0.092	0.100	0.018
4	110Г8Л	1.34	8.43	0.80	0.140	0.092	0.060	0.019
5	110Г10Л	1.24	9.75	0.48	0,017	0,092	0,100	0,019
6	110Г10Л	1.39	10.42	0.56	0.014	0.110	0.001	0.025
7	110Г10Л	1.19	10.47	0.45	0.015	0.100	0.010	0.022
8	110Г10Л	1.23	10.57	0.51	0,016	0,100	0.01	0,018
9	110Г13Л	1.35	12.91	0.76	0.009	0.090	0.180	0.018

DOI 10.15588/1607-6885-2025-1-3

Samples for mechanical testing and magnetometric studies were cut from the middle part of the ingots, which represented a homogeneous initial microstructure. Each steel grade, according to the requirements and standards, must have the corresponding indicators. But in responsible engineering, it is desirable to determine the real quality (property) of various steel melts belonging to the same grade. That is, for responsible structures, steel with the best mechanical properties should be used. It is most acceptable if the quality level of steel is determined by a single parameter, that is, without time-consuming tests.

Tensile tests were performed on a УРМ-50 machine. Microhardness was measured by a ПМТ3 device at a load of 50 g according to the standard method. The specific paramagnetic susceptibility χ_0 of austenite was determined on special high-precision equipment [10].

It should be noted that the choice of χ_0 as a criterion (indicator of mechanical properties) allows us to take into account not only the influence of the manganese content (which is the main austenitizer in the studied materials) when predicting mechanical properties, but also the influence of the content of some other elements that are part of the steel (primarily carbon).

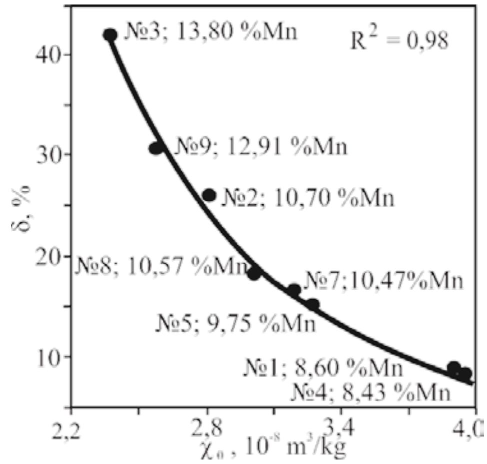
Results and discussion

During the research, many characteristics were obtained and analyzed, some of which are presented in this article. Fig. 1 shows the relationship between the atomic-magnetic state of austenite (in the initial state, i.e. before mechanical tests) and the mechanical properties of high-manganese steels. The numbers near the points coincide with the numbers of the steel samples in Table 1). With a decrease in χ_0, the plasticity index (relative elongation δ and impact toughness KCU) increase.

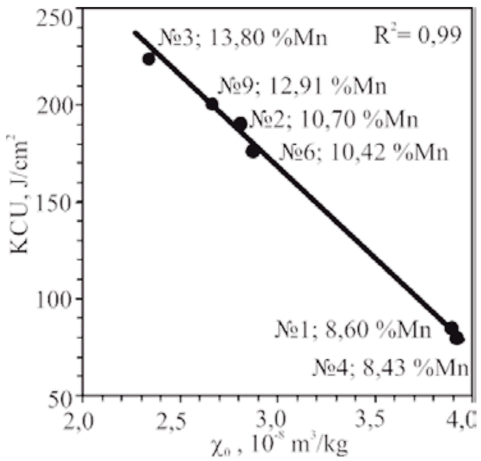
This feature in the behavior of the specified mechanical characteristics could be explained as follows. According to literature data, manganese effectively reduces the energy of stacking faults (in the specified interval of Mn content) [11]. As a result, elementary dislocations are actively split into partial ones connected by stacking faults with a crystallographic structure different from austenite.

This facilitates the process of plastic deformation due to an increase in the possibility of easy sliding, since in the case of splitting of individual elementary dislocations there is a possibility of the transition of stretched dislocations in the intersecting slip plane of the same type. Impact toughness increases with an increase in the manganese content, and therefore the stability of austenite. Low carbon, high manganese steel exhibits better impact toughness than high carbon, low manganese steel [12].

The dependence of microhardness on the magnetic state of austenite, i.e. on χ_0, is presented in Fig. 2. As can be seen, the increase in microhardness in this case correlates with the increase in the parameter χ_0.



a



b

Figure 1. Characteristics of high-manganese steels:
a – dependence of relative elongation δ;
b – impact toughness KCU on the specific paramagnetic susceptibility χ_0 of austenite (before mechanical tests)

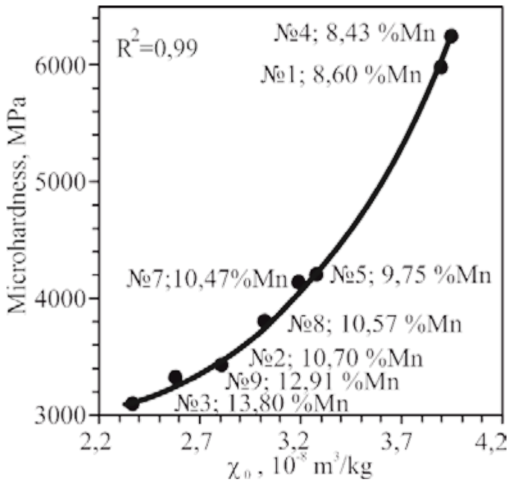


Figure 2. Relationship between microhardness and specific paramagnetic susceptibility χ_0 of austenite of high-manganese steels (numbers near the points coincide with the numbers of steels in Table 1)

DOI 10.15588/1607-6885-2025-1-3

Let us explain the above relationship as follows. Since the microhardness measurement uses loads that lead to an extremely small local deformation (when pressing the indenter), due to the very low energy of stacking faults, active splitting of full dislocations should occur, which facilitates their easy sliding and thereby significantly increases the depth of penetration of the indenter, even at low loads. At the same time, regardless of the existing lengths of the free path of dislocations at such small local deformations, stretched dislocations do not have time to create separate clusters that can significantly affect the increase in microhardness.

Analysis of the above graphs showed that there is a good correlation between the mechanical properties and the paramagnetic susceptibility of austenite, which makes it possible to use this as an effective factor in predicting the mechanical properties of an austenitic material depending on the manganese content in it (provided that the carbon content and other austenizing elements are constant).

The choice of the paramagnetic susceptibility of austenite as a criterion for evaluation the properties of steel (with varying manganese content in the steel) was also due to the fact that direct experimental determination of the mechanical properties of austenitic materials is often very time-consuming, instead, the specified criterion can be easily established using special highly sensitive equipment.

The indicated trends in property changes are reflected in the Matrix of correspondence of the direction of changes (trends) between the paramagnetic parameter χ_0 and the mechanical properties of high-manganese steels (Table 2).

Table 2 – Correspondence matrix

The tendency determined experimentally	Forecasted trends		
χ_0	δ	KCU	microhardness
↑	↓	↓	↑

Here, the signs ↑ and ↓ indicate an increase and decrease in the value, respectively.

Analysis of the results obtained (Table 2) shows that for the selection of a higher quality steel (which has better mechanical properties) it is possible to use the specific paramagnetic susceptibility χ_0 of austenite as an integral criterion. It is worth noting that the parameter χ_0 can also be used as a criterion for the level of austenite stability.

It should also be noted that the most common is the determination of the level of stability of the amount of retained austenite. Thus, in [13] maps for predicting the amount of austenite from the parameters of intercritical annealing and the initial microstructure are proposed. Process maps provide information for designing intercritical treatments of medium manganese steels, helping to optimize steel properties for automotive applications. It is generally accepted [14, 15] that the slow transformation of austenite to martensite has a beneficial effect on plasticity, so the proportion and stability of austenite should be carefully controlled.

Further research in this field involves physical-mathematical modeling to predict and determine the optimal parameters of steels.

Conclusions

1. The correlation dependence of the relative elongation δ and the impact toughness KCU on the specific paramagnetic susceptibility χ_0 of austenite (before mechanical testing) of high-manganese steels was experimentally investigated and determined.

2. A trend correspondence matrix was proposed, according to which it is possible to select a higher-quality sample of steel melt, which has better mechanical properties for the production of quality-critical products of responsible mechanical engineering.

References

1. Sun, B., Kwiatkowski da Silva, A., Wu Y., et al. (2023). Physical metallurgy of medium-Mn advanced high-strength steels. International Materials Reviews, 68, 7, 786–824. DOI: https://doi.org/10.1080/09506608.2022.2153220

2. Snizhnoi, H., Sazhnev, V., Snizhnoi, V., Mukhachev, A. (2024). Details of mining beneficiation equipment made of medium manganese wear-resistant steel. IOP Conference Series: Earth and Environmental Science, 1348, art. no. 012027. DOI: https://doi.org/10.1088/1755-1315/1348/1/012027

3. Sazhnev, V. M., Snizhnoi, H. (2023). The influence of technological parameters on the physical, mechanical and operational properties of wear-resistant austenitic high-mannan steel. Metallofizika i Noveishie Tekhnologii, 45, 4, 503–522. DOI: https://doi.org/10.15407/mfint.45.04.0503

4. Varela, L.B., Tressia, G., Masoumi M., Bortoleto, E.M., Regattieri C., Sinatora, A. (2021). Roller crushers in iron mining, how does the degradation of Hadfield steel components occur? Engineering Failure Analysis, 122, art. no. 105295. DOI: 10.1016/j.engfailanal.2021.105295

5. Gürol U., Kurnaz S. (2020). Effect of carbon and manganese content on the microstructure and mechanical properties of high manganese austenitic steel. Journal of Mining and Metallurgy, Section B: Metallurgy, 56, 2, 171–182. DOI: https://doi.org/10.2298/ JMMB191111009G

6. Yan J., Zhou M., Wu H., Liang X., Xing Z., Li H., Zhao L., Jiao S., Jiang Z. (2023). A Review of Key Factors Affecting the Wear Performance of Medium Manganese Steels. Metals, 13, 7, art. no. 1152. DOI: https://doi.org/10.3390/met13071152

7. Torabi, S. A., Amini, K., Naseri, M. (2017). Investigating the Effect of Manganese Content on the Properties of High Manganese Austenitic Steels /, international journal of advanced design and manufacturing technology (Int J Advanced Design and Manufacturing Technology), 10, 1, 75–83.

8. Kurylyak, V. V., Khimicheva, G. I. (2017). Zastosuvannya kvalimetry`chny`x metod dlya ocinyuvannya yakosty` udarno-navantazheny`x materiyaliv [Application of qualimetric methods for evaluation test of shock-loaded materials. Uspixy` fizy`ky` metaliv – Progress in Physics

DOI 10.15588/1607-6885-2025-1-3

of Metals, 18, 2, 155–175. DOI: https://doi.org/10.15407/ufm.18.02.155

9. Snizhnoi, G. V. Rasshchupkyna, M. S. (2012). Magnetic state of the deformed austenite before and after martensite nucleation in austenitic stainless steels. Journal of Iron and Steel Research, International. 19, 6, 42–46. DOI: https://doi.org/10.1016/S1006-706X(12)60125-3

10. Vasylenko, O., Reva, V., Snizhnoi, G. (2019). Simulation of ACS for Magnetic Susceptibility Measurements in ECAD Based on Time Domain Functions. Proceedings of the Second International Workshop on Computer Modeling and Intelligent Systems, CEUR Workshop Proceedings, 2353, 689-701. DOI: https://doi.org/10.32782/cmis/2353–55.

11. Ol'shanetskii, V. E., Snezhnoi, G. V., Sazhnev, V. N. (2016). Structural and magnetic stability of austenite in chromium-nickel and manganese steels with cold deformation, Metal science and heat treatment, 58, 5–6, 311–317. DOI: 10.1007/s11041-016-0009-5

12. Ankita Bhattacharya, Sankalp Biswal, Rakesh Kumar Barik, Bhupeshwar Mahato, Mainak Ghosh, Rahul Mitra, Debalay Chakrabarti (2024). Comparative interplay of C and Mn on austenite stabilization and low temperature impact toughness of low C medium Mn steels. Materials Characterization, 208, art. no. 113658, ISSN 1044-5803, DOI: https://doi.org/10.1016/ j.matchar.2024.113658.

13. Mehrabi, A., Zurob, H.S., McDermid, J.R. (2024). Process Maps for Predicting Austenite Fraction (vol.%) in Medium-Mn Third-Generation Advanced High-Strength Steels. Materials, 17, 5, art. no. 993. DOI: https://doi.org/10.3390/ma17050993

14. Vung Lam Nuam, Zhang Hao, Xiong Zhi-ping. (2024). Role of retained austenite in advanced high-strength steel: ductility and toughness. Journal of Iron and Steel Research International, 31. DOI: https://doi.org/10.1007/s42243-023-01165-3

15. Ning Guo, Renjie Chen, Jiyuan Liu, Bingtao Tang, Guangchun Xiao (2024). Plasticity enhancement and sustainable strain hardening mechanism of a novel developed medium Mn steel, Materials Letters, 364, art. no.136388, ISSN 0167-577X, DOI: https://doi.org/10.1016/j.matlet.2024.136388.

Одержано 12.03.2025

КОНТРОЛЬ ЯКОСТІ ВИСОКОМАНГАНОВИХ СТАЛЕЙ ЗА ПАРАМАГНЕТНИМ СТАНОМ АУСТЕНІТУ

Вадим Ольшанецький — д-р техн. наук, професор кафедри фізичного матеріалознавства, Національний університет «Запорізька політехніка», Запоріжжя, Україна, *e-mail: olshan@zp.edu.ua*, ORCID: 0000-0002-9485-4896

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 і технології ливарного виробництва, Національний університет «Запорізька політехніка», Запоріжжя, Україна, *e-mail: sajhnev@zp.edu.ua*, ORCID: 0000-0002-2095-4958

Ольга Василенко — канд. техн. наук, доцент, доцент кафедри інформаційної безпеки та наноелектроніки, Національний університет «Запорізька політехніка», Запоріжжя, Україна, *e-mail: drvasylenkoolga@gmail.com*, ORCID: 0000-0001-6535-3462

Денис Онищенко — аспірант гр. А-132 Національний університет «Запорізька політехніка», Запоріжжя, Україна, *e-mail: denys.onyshchenko@zp.edu.ua*, ORCID: 0009-0008-4766-7052

Мета роботи. *Визначення методики для комплексної оцінки механічних властивостей високоманганових сталей за одним параметром, який є чутливим до впливу зовнішніх факторів, що сприятиме зменшенню витрат на лабораторні дослідження під час відбору найкращих зразків (плавок) сталей для виготовлення критичних до якості виробів відповідального машинобудування.*

Методи дослідження. *Випробування на розрив проводили на машині УРМ-50, відносне видовження визначали за стандартною методикою. Мікротвердість вимірювали з використанням приладу ПМТ3 при навантаженні 50 г за стандартною методикою. Визначення питомої парамагнетної сприйнятливості* χ_0 *аустеніту (до механічних випробувань) здійснювали на автоматизованих магнетометричних терезах.*

Отримані результати. *Виходячи з результатів експериментальних досліджень, встановлено наявність кореляції між механічними властивостями і питомою парамагнетною сприйнятливістю* χ_0 *аустеніту. Параметр* χ_0 *є характеристикою атомно-магнетного стану аустеніту і є надчутливою величиною до впливу різно-*

DOI 10.15588/1607-6885-2025-1-3

манітних зовнішніх факторів. Саме тому запропоновано використовувати питому парамагнетну сприйнятливість χ_0 аустеніту як інтегральну характеристику для визначення впливу різноманітних факторів (хімічний склад, умови виплавлення, деформація, температура тощо) на властивості сталі.

Наукова новизна. *Запропоновано й експериментально підтверджено ідею про зв'язок між механічними властивостями аустенітних сталей і попередньо сформованим атомно-магнетним станом аустенітної матриці.*

Практична цінність. *Визначений кореляційний зв'язок між механічними властивостями високоманганових сталей і питомою парамагнетною сприйнятливістю χ_0 аустеніту та запропонована матриця відповідності тенденцій обумовлюють можливість експрес-прогнозування та контроль якості сталей без проведення трудомістких механічних випробувань.*

Ключові слова: *аустеніт, подовження, зносостійкість, мартенсит деформації, парамагнетна сприйнятливість.*

Список літератури

1. Physical metallurgy of medium-Mn advanced high-strength steels / Sun, B., Kwiatkowski da Silva, A., Wu Y., et al. // International Materials Reviews. – 2003. – Vol. 68. – no 7. – P. 786–824. DOI: https://doi.org/ 10.1080/09506608.2022.2153220

2. Details of mining beneficiation equipment made of medium manganese wear-resistant steel. IOP Conference Series: Earth and Environmental Science / Snizhnoi, H., Sazhnev, V., Snizhnoi, V., Mukhachev, A. – 2024. – 1348, art. no. 012027. DOI: https://doi.org/10.1088/1755-1315/1348/1/012027

3. Sazhnev, V. M. The influence of technological parameters on the physical, mechanical and operational properties of wear-resistant austenitic high-mannan steel / Sazhnev, V. M., Snizhnoi, H. // Metallofizika i Noveishie Tekhnologii. – 2023. – Vol. 45. – No 4. – P. 503–522. DOI: https://doi.org/10.15407/mfint.45.04.0503

4. Roller crushers in iron mining, how does the degradation of Hadfield steel components occur? / Varela, L.B., Tressia, G., Masoumi M. et al. // Engineering Failure Analysis. – 2021. – 122 art. – no. 105295. DOI: 10.1016/j.engfailanal.2021.105295.

5. Gürol U. Effect of carbon and manganese content on the microstructure and mechanical properties of high manganese austenitic steel / Gürol U., Kurnaz S. // Journal of Mining and Metallurgy, Section B: Metallurgy. – 2020. – Vol. 56. – No 2. – P. 171–182. DOI: https://doi.org/10.2298/ JMMB191111009G

6. A Review of Key Factors Affecting the Wear Performance of Medium Manganese Steels / Yan J., Zhou M., Wu H. and al. // Metals. – 2023. – Vol. 13. – No 7, art. 1152. DOI: https://doi.org/10.3390/met13071152

7. Torabi, S. A. Investigating the Effect of Manganese Content on the Properties of High Manganese Austenitic Steels / Torabi, S. A., Amini, K., Naseri, M. // International journal of advanced design and manufacturing technology (Int J Advanced Design and Manufacturing Technology). – 2017. – Vol. 10. – no 1. – P. 75–83.

8. Kurylyak, V. V., Khimicheva, G. I. (2017). Zastosuvannya kvalimetry`chny`x metod dlya ocinyuvannya yakosty` udarno-navantazheny`x materiyaliv [Application of qualimetric methods for evaluation test of shock-loaded materials. Uspixy` fizy`ky` metaliv – // Progress in Physics of Metals. – 2017. – Vol. 18. – no 2. – P. 155–175. DOI: https://doi.org/10.15407/ ufm.18.02.155

9. Snizhnoi, G. V. Magnetic state of the deformed austenite before and after martensite nucleation in austenitic stainless steels / Snizhnoi, G. V. Rasshchupkyna, M. S. // Journal of Iron and Steel Research, International. – 2012. – Vol. 19. – no 6. – P. 42–46. DOI: https://doi.org/10.1016/S1006-706X(12)60125-3

10. Vasylenko, O. Simulation of ACS for Magnetic Susceptibility Measurements in ECAD Based on Time Domain Functions / Vasylenko, O., Reva, V., Snizhnoi, G.// Proceedings of the Second International Workshop on Computer Modeling and Intelligent Systems, CEUR Workshop Proceedings. – 2019. – 2353. – P. 689–701. DOI: https://doi.org/10.32782/cmis/2353–55.

11. Structural and magnetic stability of austenite in chromium-nickel and manganese steels with cold deformation / Ol'shanetskii, V. E., Snezhnoi, G. V., Sazhnev, V. N. // Metal science and heat treatment. – 2016. – Vol. 58. – no 5–6. – P. 311–317. DOI: 10.1007/s11041-016-0009-5

12. Comparative interplay of C and Mn on austenite stabilization and low temperature impact toughness of low C medium Mn steels / Ankita Bhattacharya, Sankalp Biswal, Rakesh Kumar Barik et al. // Materials Characterization. – 2024. – 208, art. no. 113658, ISSN 1044-5803, DOI: https://doi.org/10.1016/ j.matchar.2024.113658.

13. Mehrabi, A. Process Maps for Predicting Austenite Fraction (vol.%) in Medium-Mn Third-Generation Advanced High-Strength Steels / Mehrabi, A., Zurob, H.S., McDermid, J.R. // Materials. – 2024. – 17, 5, art. no. 993. DOI: https://doi.org/ 10.3390/ma17050993

14. Vung Lam Nuam. Role of retained austenite in advanced high-strength steel: ductility and toughness / Vung Lam Nuam, Zhang Hao, Xiong Zhi-ping // Journal of Iron and Steel Research International. – 2024, 31. DOI: https://doi.org/10.1007/s42243-023-01165-3

15. Plasticity enhancement and sustainable strain hardening mechanism of a novel developed medium Mn steel / Ning Guo, Renjie Chen, Jiyuan Liu et al. // Materials Letters. – 2024. – 364, art. no.136388, ISSN 0167-577X, DOI: https://doi.org/10.1016/j.matlet.2024.136388.

DOI 10.15588/1607-6885-2025-1-3