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MODERN APPROACH TO DETERMINING THE HETEROGENEITY OF CAST IRON

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Abstract. *In the process of designing and optimizing materials for industrial applications, there is a need for a comprehensive analysis of their mechanical properties. Some of these properties, by their physical nature, have opposite growth trends. In particular, an increase in the hardness of iron-carbon alloys is accompanied by a decrease in plasticity and an increase in brittleness, which makes it difficult to achieve an optimal balance between these characteristics. In this regard, the task of assessing the area that defines the limits of the combination of mechanical properties, or the so-called compromise area, arises. For the study, short-rolling rolls produced by the USSR Steel Mill were selected, and the sample was based on 283 melts with a total mass of over 800 tons. Analysis of cast iron rolls manufactured using the SSCHN technology allowed us to determine the compromise area, which includes the ranges of permissible values of mechanical properties: tensile strength (σB) within 240–460 MPa, bending strength ($\sigma_{ЗГИН}$) in the range of 330–940 MPa, impact strength (KS) from 9 to 33 kJ/m² and Shore hardness (HSD) within 40–60 units. These values were obtained taking into account the full range of material cooling parameters in metal molds. The proposed method for assessing the compromise area makes it possible to set priorities regarding the set of mechanical characteristics of rolls required by the consumer, to predict changes in the parameters of the technological process and to carry out its adaptive adjustment. In particular, the methodology provides for the possibility of automated regulation of the chemical composition of the material in accordance with the specified operating conditions.*

Keywords: *carbon alloys, multiracial, structure, hardness, statistical dimensions, orderliness, regularity.*

Introduction

Establishing the relationship between the structure and quality criteria of materials is one of the main tasks of materials science. However, the real structure of many materials has a complex morphology [1–3]. Such structures include the surfaces of materials after various types of spraying, heat treatment, non-metallic inclusions, etc. [4–7].

Analysis of publications

The structure of iron-carbon alloys, which is formed as a result of the decomposition of austenite, has a complex geometric configuration. For the quantitative identification of such structural elements as martensite, bainite, pearlite, carbides, and interphase boundaries, the language of fractal geometry [8–10], in particular multifractal theory, is successfully used [11, 12].

Multifractal theory is a powerful tool for analyzing heterogeneous structures that exhibit complex hierarchical organization at different scales. In materials science, its application allows for a deeper understanding of the relationship between a material's microstructure and its macroscopic properties.

Materials often have complex morphology due to random or deterministic processes of crystal grain growth, porosity, impurity distribution, etc. [13–16]. Multifractal analysis allows:

- assess the non-uniformity of phase distribution in composites, metals and ceramics;
- to identify patterns in the distribution of pores in porous materials;
- describe the multiscale organization of grains in polycrystals.

Thanks to the multifractal approach, it is possible to quantitatively assess the mechanical heterogeneity of a material, which directly affects its strength, plasticity and fracture resistance. For example, the analysis of the multifractal stress spectrum in materials allows predicting their resistance to fatigue fracture; identifying patterns of local plastic deformation in metal alloys.

The multifractal approach is effective in studying the topography of materials, especially when analyzing surfaces that have undergone wear, corrosion, or other degradation processes: studying the structure of surface defects in thin films, assessing wear and surface roughness of structural materials, and studying the dynamics of corrosion destruction of metals.

Multifractal theory provides a wide range of tools for the analysis of complex structures in materials science. It allows not only to quantitatively assess the heterogeneity of materials, but also to establish regularities between their micro- and macrostructure. This opens up new opportunities for predicting the mechanical, electrophysical and other operational characteristics of materials, which is important for the creation of new high-performance materials with specified properties [17–19].

Purpose and statement of the task

In view of the above, the main goal of this study is to apply the fractal approach to analyze the heterogeneity of the surface structure of carbon alloys, as well as to establish the relationship between the spectrum of dimensions of structural elements and the mechanical characteristics of the material. To achieve this goal, the following tasks were solved:

1 study of interphase boundaries and morphological features of the alloy structure;

2 assessment of the level of material heterogeneity using multifractal analysis;

3 determination of correlations between multifractal characteristics of the structure and alloy hardness.

Material and research methods

Carbon alloy samples with the chemical composition (Table 1) were studied.

Table 1 – Chemical composition of carbon alloy

C	Si	Mn	P	S	Cr
2.95	1.22	0.56	0.034	0.012	0.63
Ni	Mo	Cu	V	Mg	-
3.55	0.43	0.10	0.008	0.058	-

The microstructure of the samples was analyzed using a Neophot 2 optical microscope, and the resulting images were captured with an Olympus C-50 digital camera with a resolution of 2288×1712 pixels. This allowed us to obtain detailed images necessary for further processing and analysis.

The images were presented in BMP format with 256 grayscale levels, which provides sufficient color depth for analyzing the heterogeneity of the material structure. The use of the gray color spectrum allows for a more accurate assessment of interfacial boundaries, microdefects, and the distribution of structural components.

Fig. 1 shows the microstructure of SShKhNM-55 cast iron after multi-stage heat treatment.

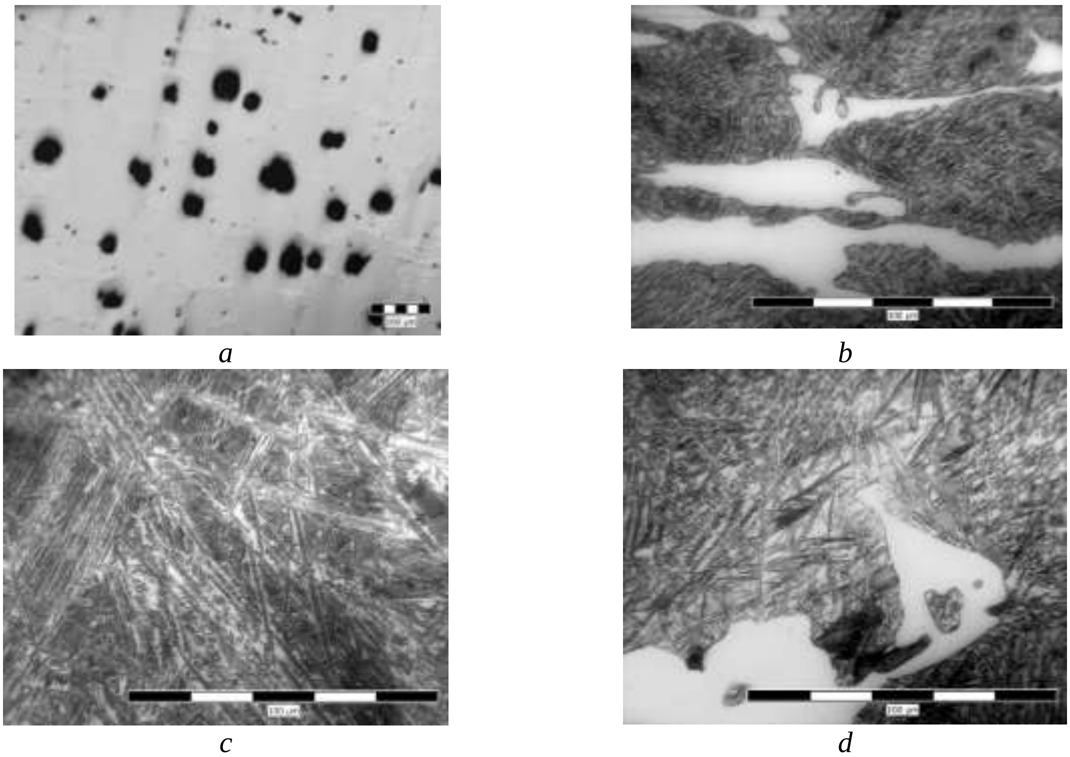


Fig. 1. Microstructure of carbon alloy: a – spheroidal graphite ~3%; b – matrix: Bainite + Martensite + Cementite (~18%); c – matrix: Martensite + Pearlite (~5%) + Cementite (~13%); d – matrix: Martensite + Bainite + Sorbite-like Pearlite + Cementite (~13)

The obtained microstructure images will be used for further multifractal analysis, which will allow establishing quantitative characteristics of the material heterogeneity and the relationship between the dimensional spectrum and the mechanical properties of the alloy.

Experimental results and their discussion

Multifractal analysis is based on the assessment of statistical characteristics of elements of a metal structure, which are calculated on the basis of the spectrum of statistical dimensions of the Renyi D(q). It allows to determine the most significant contribution to the statistical sum $\sum_{i=1}^{N} p_i^q$ for given values of the exponent q. This statistical sum reflects the probability distribution over all points of the studied surface [20]:

$$D(q) = \frac{1}{q-1} \lim_{\varepsilon \to \infty} \frac{\ln \sum_{i=1}^{N} p_i^q}{\ln \varepsilon}, \qquad (1)$$

where p_i is the probability of detecting the studied point (computer pixel) belonging to the object in the i -th cell of a square grid of size ε. In this work, the value of the exponent q varied from -300 to 300.

To determine the degree of heterogeneity of the structure, the spectrum of singularities f(α) was calculated: This spectrum is described by the filling of square cells ε with equal probabilities $p_i(\varepsilon) \approx \varepsilon^{\alpha}$.

$$\begin{cases} \alpha = \dfrac{d\tau(q)}{dq}, \\ f(\alpha) = q\alpha - \tau(q) \end{cases} \qquad (2)$$

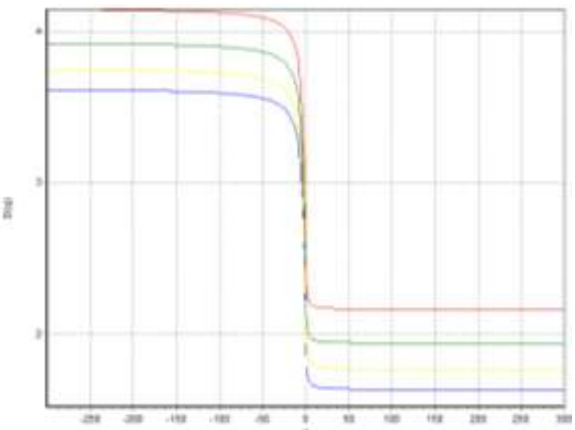
The spectrum $f(\alpha)$ was calculated by performing the Legendre transform of the function $\tau(q)$.

Based on the results of the analysis of the spectrum of statistical dimensions D(q)D(q)D(q) and the spectrum of singularities f(α), the following statistical characteristics of the structure were calculated:

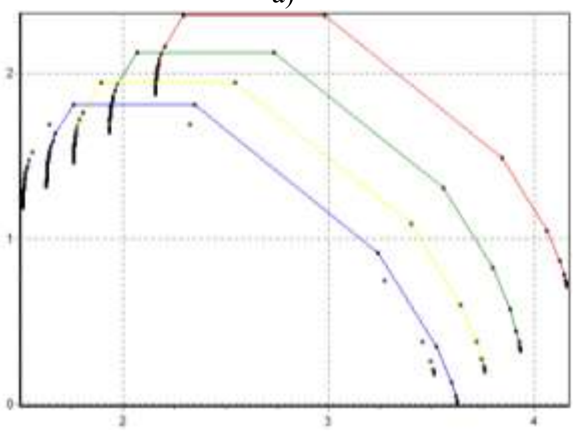
- the heterogeneity of the structure is determined by the uneven distribution of points over the regions into which the structure is divided, i.e. its geometrically identical elements are filled with points with different probabilities. In this case, the left or right part of the spectrum f(α) is different from zero. From the point of view of materials science, such heterogeneity determines the local defectivity of the studied structure, its porosity or roughness of individual elements;

- orderliness $\Delta = D_1 - D_{300}$ and regularity $K = D_{-300} - D_{300}$. Dimensionality D_1 is called information dimension and is calculated from the spectrum of dimensions at q =1. These characteristics describe the degree of symmetry breaking in the structure or the level of non-equilibrium state of the system. The higher the numerical values of the indices Δ and K, the greater the content of periodic components (repeating structural elements of one phase) in the structure, and therefore, the more ordered it is.

Fig. 2 presents the results of calculations of the spectra of functions $D(q)$ and $f(\alpha)$ for the microstructure of the carbon alloy.



a)



б)

Fig. 2. Spectrum of statistical dimensions of Renyi D(q) (a) and heterogeneity f(α) (b) of the carbon alloy structure

Statistical dimensions structures D_{-300} changed from 4.18 to 2.47 (Fig. 3), which indicates the compactness of filling the space with martensite, bainite, pearlite. The indicators of the statistical dimensionality of cementite are described by the dimension D_{300}, which are in the range from 2.18 to 1.55. Fractal D_0, information D_1, correlation D_2 dimensions of martensite, bainite, pearlite also changed in a wide range of dimensions (Fig. 3).

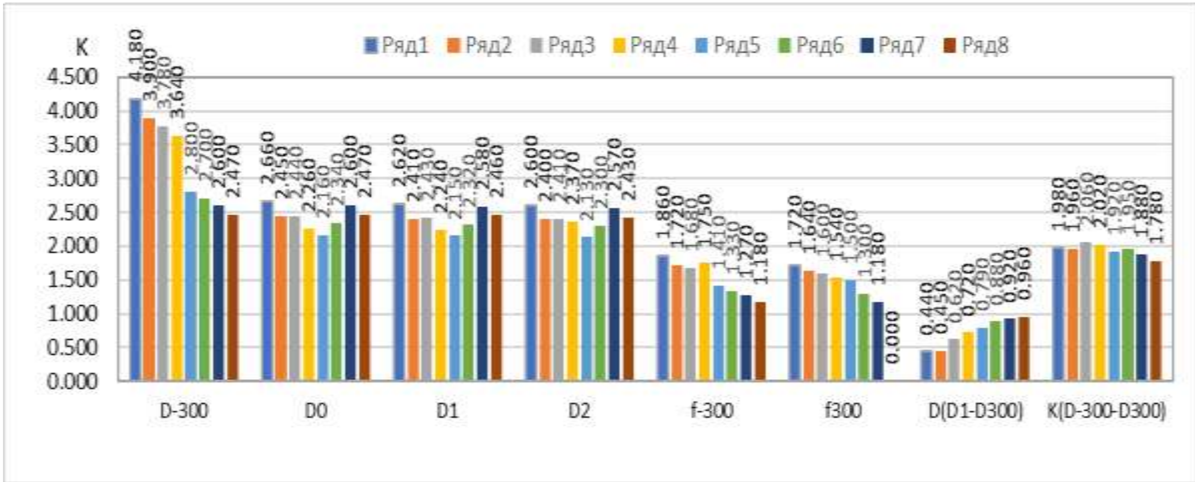


Fig. 3. Multifractal indicators of the heterogeneity of the structure of a carbon alloy

Inhomogeneity indices of martensite, bainite, pearlite f_{-300} changed from values of 1.18 to 1.86, the indices of cementite heterogeneity f_{-300} varied from 0 to 1.72 (Fig. 3).

Multiparametric model describing the influence of the indicators of heterogeneity and fractality of the structure on the hardness indicators:

$$HSD = 60.05 + 12,42 \cdot D_{600} + 3,429 \cdot D_{600} - 1.57 \cdot \Delta - 32.62 \cdot K - 2.14 \cdot D_0 + 0.85 \cdot D_1 - 3.45 \cdot D_0 \quad R^2 = 0.89.$$

The obtained results indicate the possibility of identifying complex geometrically and heterogeneous structures of carbon alloys after multi-stage thermal treatment.

Conclusions

During the work, the following results were obtained:

1 the interphase boundaries and morphological features of the carbon alloy structure were investigated, indicating a fractal structure and a complex configuration of structural elements, which are difficult to describe using Euclidean geometry;

2 assessment of the level of material heterogeneity using multifractal analysis;

3 a mathematical model has been constructed that describes the dependence of multifractal indicators of the structure and hardness of the alloy with the pair correlation coefficient $R^2 = 0.89$.

Література

1. Rogovyi S., Khovanskyy I., Grechka J. Pitel. *Lecture Notes in Mechanical Engineering. 2020.* 682–691. https://doi.org/10.1007/978-3-030-22365-6_68
2. Vynogradov O. M. Reduction of costs for foundry production. *Casting of Ukraine*. 2005. 3. 5–8.
3. Rogovyi A. *Energy*. 2018. 163. 52–60. https://doi.org/10.1016/j.energy.2018.08.075
4. Maslova V., Nastase R., Veryasov G., Nesterenko N., Fourré E., Batiot-Dupeyrat C. *Progress in Energy and Combustion Science*. 2024. 101. 101096. https://doi.org/10.1016/j.pecs. 2023. 101096
5. Batygin Y. V., Golovashchenko S. F., Gnatov A. V. *Journal of Materials Processing Technology*. 2013. 213(3). 444–452. http://dx.doi.org/10.1016 / j.jmatprotec.2012.10.003
6. Andrenko P., Rogovyi A., Hrechka I., Khovanskyi S., Svynarenko M. *Journal of Physics: Conference Series*, 2021. 1741(1). https://doi.org/10.1088/1742-6596/1741/1/012024
7. Gladkikh L. I., Malykhyn S. V., Pugache A. T., Reshetnyak O. M., Glushkova D. B., D'Yachenko S. S., Kovtun G. P. Metallofizika i Noveishie Tekhnologii. 2003. 6(25). 763–776.
8. Zhang P., Ding J., Guo J., Wang F. *Fractal and Fractional*. 2024. 8(6). 304. https://doi.org/ 10.3390/ fractalfract8060304
9. Vafaeva K. M., Zegait R. *Research he Engineering Structures and Materials*. 2024. 10(2). 559. http://dx.doi.org/10.17515/resm 2023.42 ma0818rv
10. Volchuk V. M., Uzlov O. V., Puchikov O. V., Ivantsov S. V. *IOP Conference Series: Materials Science and Engineering*, 1021(1). 012053, IOP Publishing, 2021. https://doi.org/10.1088/1757-899X/1021/1/012053
11. Hlushkova D. B., Kalinin A. V., Kalinina N. E., Volchuk V. M., Saenko V. A., Efimenko A. A. Problems of Atomic Science and Technology. 2023. 144(2). 126. https://doi.org/10.46813/ 2023-144-126
12. Kakimzhanov D., Rakhadilov B., Sulyubayeva L., Dautbekov M. *Coatings*. 2023. 13(11). 1824.
13. Hlushkova D. B., Bagrov V. A., Saenko V. A., Volchuk V. M., Kalinin A. V., Kalinina N. E. *Problems of Atomic Science and Technology*.

2023. 144(2). 105. https://doi.org/10.46813/2023-144-105

14. Hlushkova D. B., Volchuk V. M., Polyansky P. M., Saenko V. A., Efimenko A. A. *Functional Materials*. 2023. 30(2). 275. https://doi.org/10.15407 /fm30.02.275
15. Hlushkova D. B., Volchuk V. M. *Functional Materials*. 2023. 30(3). 453 (2023) https://doi.org/ 10.15407/fm30.03.453
16. Wang Y., Karasev A., Park J. H., Jönsson P. G. *Metall Mater Trans. 2021*. B 52. 2892–2925. https://doi.org/10.1007/s11663-021-02259-7
17. Yanchuk V., Kruhlov I., Zakiev V., Lozova A., Trembach B., Orlov A., Voloshko S. Metallofiz Noveishie Tekhnol. 2022. 44(10). 1275–1292. https://doi.org/10.15407/mfint.44.10.1275
18. Rogovyi A., Korohodskyi V., Khovanskyi S., Hrechka I., Medvediev Y. *Journal of Physics: Conference Series*. 2021. 1741(1). https://doi.org/10.1088/1742-6596/1741/1/012018
19. Hlushkova D. B., Ryzhkov Yu. V., Kostina L. L., Demchenko S. V. *Problems of Atomic Science and Technology*. 2018. 1(113). 208–211.
20. Reddivari B. R., Vadapalli S., Sanduru B., Buddi T., Vafaeva K. M., Joshi A. *Cogent Engineering*. 2024. 11(1). 2343586 https://doi.org/10.1080 / 23311916.2024.2343586

References

1. Rogovyi, S., Khovanskyy, I., Grechka, J. Pitel. (2020). *Lecture Notes in Mechanical Engineering. 2020*. 682–691. https://doi.org/ 10.1007/ 978-3-030-22365-6_68
2. Vynogradov, O. M. (2005). Reduction of costs for foundry production. *Casting of Ukraine*. 3. 5–8.
3. Rogovyi, A. (2018). *Energy*. 163. 52–60. https://doi.org/10.1016/j.energy.2018.08.075
4. Maslova, V., Nastase, R., Veryasov, G., Nesterenko, N., Fourré, E., Batiot-Dupeyrat C. (2024). *Progress in Energy and Combustion Science*. 101. 101096. https://doi.org/10.1016/ j.pecs.2023. 101096
5. Batygin, Y. V., Golovashchenko, S. F., Gnatov, A. V. *(2013). Journal of Materials Processing Technology*. 213(3). 444–452. http://dx.doi.org/ 10.1016/j.jmatprotec.2012.10.003
6. Andrenko, P., Rogovyi, A., Hrechka, I., Khovanskyi, S., Svynarenko, M. (2021). *Journal of Physics: Conference Series*. 1741(1). https://doi.org/10.1088/1742-6596/1741/1/012024
7. Gladkikh, L. I., Malykhyn, S. V., Pugache, A. T., Reshetnyak, O. M., Glushkova, D. B., D'Yachenko, S. S., Kovtun, G. P. (2003). Metallofizika i Noveishie Tekhnologii. 6(25). 763–776.
8. Zhang, P., Ding, J., Guo, J., Wang, F. (2024). *Fractal and Fractional*. 8(6). 304. https://doi.org/10.3390/fractalfract8060304
9. Vafaeva, K. M., Zegait, R. (2024). *Research he Engineering Structures and Materials*. 10(2). 559. http://dx.doi.org/10.17515/resm2023.42ma0818rv
10. Volchuk, V. M., Uzlov, O. V., Puchikov, O. V., Ivantsov, S. V. (2021). *IOP Conference Series: Materials Science and Engineering*. 1021(1). 012053, IOP Publishing. https://doi.org/ 10.1088/1757-899X/1021/1/012053
11. Hlushkova, D. B., Kalinin, A. V., Kalinina, N. E., Volchuk, V. M., Saenko, V. A., Efimenko, A. A. (2023). Problems of Atomic Science and Technology. 144(2). 126 https://doi.org/ 10.46813/ 2023-144-126
12. Kakimzhanov, D., Rakhadilov, B., Sulyubayeva, L., Dautbekov, M. (2023). *Coatings*. 13(11). 1824.
13. Hlushkova, D. B., Bagrov, V. A., Saenko, V. A., Volchuk, V. M., Kalinin, A. V., Kalinina, N. E. (2023). *Problems of Atomic Science and Technology*. 144(2). 105. https://doi.org/ 10.46813/2023-144-105
14. Hlushkova, D. B., Volchuk, V. M., Polyansky, P. M., Saenko, V. A., Efimenko, A. A. (2023). *Functional Materials*. 30(2). 275. https://doi.org/ 10.15407/fm30.02.275
15. Hlushkova, D. B., Volchuk, V. M. (2023). *Functional Materials*. 30(3). 453 (2023) https://doi.org/10.15407/fm30.03.453
16. Wang, Y., Karasev, A., Park, J. H., Jönsson, P. G (2021). *Metall Mater Trans. 2021*. B 52. 2892–2925. https://doi.org/10.1007/s11663-021-02259-7
17. Yanchuk, V., Kruhlov, I., Zakiev, V., Lozova, A., Trembach, B., Orlov, A., Voloshko, S. (2022). Metallofiz Noveishie Tekhnol. 2022. 44(10). 1275–1292. https://doi.org/10.15407/mfint.44.10.1275
18. Rogovyi, A., Korohodskyi, V., Khovanskyi, S., Hrechka, I., Medvediev, Y. (2021). *Journal of Physics: Conference Series*. 1741(1). https://doi.org/10.1088/1742-6596/1741/1/012018
19. Hlushkova, D. B., Ryzhkov, Yu. V., Kostina, L. L., Demchenko, S. V. (2018). *Problems of Atomic Science and Technology*. 1(113). 208–211.
20. Reddivari, B. R., Vadapalli, S., Sanduru, B., Buddi, T., Vafaeva, K. M., Joshi, A. (2024). *Cogent Engineering*. 11(1). 2343586 https://doi.org/10.1080/23311916.2024.2343586

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Сучасний підхід до визначення неоднорідності чавуну

Анотація. Постановка проблеми. *У процесі проєктування та оптимізації матеріалів для про-*

мислового застосування виникає необхідність у комплексному аналізі їхніх механічних властивостей. Деякі з цих властивостей за своїми фізичними властивостями мають протилежні тренди збільшення, зокрема, підвищення твердості залізовуглецевих сплавів супроводжується зниженням пластичності та збільшенням крихкості, що ускладнює досягнення оптимального балансу між цими характеристиками. У зв'язку з цим актуальним є завдання аналізу області, що визначає межі поєднання механічних властивостей, тобто так званої сфери компромісу. ***Мета та задачі дослідження.*** *З огляду на вищезазначене основною метою цього дослідження є застосування фрактального підходу для аналізу неоднорідності структури поверхні вуглецевих сплавів, а також визначення зв'язку між спектром розмірів елементів конструкції та механічними характеристиками матеріалу. Для досягнення поставленої мети вирішувалися такі завдання: 1 дослідження міжфазних меж і морфологічних особливостей структури сплаву; 2 визначення рівня неоднорідності матеріалу за допомогою мультифрактального аналізу; 3 визначення кореляційних зв'язків між мультифрактальними характеристиками структури та твердістю сплаву.* ***Матеріали та методики дослідження.*** *Для проведення дослідження було вибрано сортопрокатні валки виробництва СШХН, їх вибір здійснювався на основі 283 плавок із загальною масою більше ніж 800 тонн.* ***Результати досліджень та їх обговорення.*** *Аналіз чавунних валків, виготовлених за технологією СШХН, дозволив визначити область компромісу, яка містить діапазони допустимих значень механічних властивостей: межа міцності під час розтягування (σB) – у межах 240–460 МПа, межа міцності під час згинання ($\sigma_{згин}$) – у діапазоні 330–940 МПа, ударна в'язкість (KC) – від 9 до 33 кДж/м² та твердість за шкалою Шора (HSD) – у межах 40–60 одиниць. Ці значення отримані з огляду на діапазон параметрів охолодження матеріалу в металевих формах. Запропонований метод аналізу області компромісу дає змогу визначити пріоритети щодо необхідного для споживача комплексу механічних характеристик валків, спрогнозувати зміну параметрів технологічного процесу та здійснити його адаптивне коригування. Методологія передбачає можливість автоматизованого регулювання хімічного складу матеріалу відповідно до заданих експлуатаційних умов.* ***Висновки.*** *Під час роботи були отримані такі результати: 1 досліджено міжфазні межі та морфологічні особливості структури вуглецевого сплаву, що вказують на фрактальну структуру та складну конфігурацію структурних елементів, які важко описати за допомогою евклідової геометрії; визначено рівень гетерогенності матеріалу за допомогою мультифрактального аналізу; побудовано математичну модель залежності мультифрактальних показників структури та твердості сплаву з парним коефіцієнтом кореляції $R^2 = 0,89$.*

Ключові слова: *вуглецеві сплави, мультифрактал, структура, твердість, статистичні розмірності, впорядкованість, регулярність.*

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