DOI: https://doi.org/10.37434/tpwj2025.11.05

USE OF THE HOUGH TRANSFORMATION METHOD FOR THE METALLOGRAPHIC STUDIES OF FERRITIC-BAINITIC STEELS MICROSTRUCTURE

V.V. Holovko[1], **O.O. Shtofel**[1,2], **D.Yu. Korolenko**[1]

[1]E.O. Paton Electric Welding Institute of the NASU
11 Kazymyr Malevych Str., 03150, Kyiv, Ukraine
[2]National Technical University of Ukraine "Igor Sikorsky Kyiv Polytechnic Institute"
37 Prosp. Beresteiskyi, 03056, Kyiv, Ukraine

ABSTRACT

High-strength low-alloy steels are a promising material for the manufacture of welded metal structures, but their widespread use is hampered by their increased susceptibility to defects that arise during the welding process. Therefore, a fundamental aspect of developing the technology for welding these steels is understanding how the properties of the metal change during the welding process and identifying the main microstructural characteristics that explain these changes. Research on high-strength ferritic-bainitic steels, which concerns the microstructural characteristics and mechanical properties, is aimed at determining the total angle of structural grains misorientation, using the electron backscatter diffraction (EBSD) method, which can be implemented on electron microscopes, and requires special software installation. The metallographic analysis method using the Hough transformation, which can be implemented on optical microscopes and does not require special software, should be considered as an alternative to the EBSD method.

KEYWORDS: high-strength low-alloy steel, welding, microstructure, metallographic analysis, grain boundaries, structural grains misorientation, Hough transformation

INTRODUCTION

Recently, in Ukrainian industry, there has been a significant increase in the volume of work involving the use of high-strength low-alloy steels (HSLA) manufactured at leading metallurgical enterprises in the EU, Great Britain, USA, and Canada. Working with such materials presents new challenges for both industrial engineers and researchers. Preliminary results have shown that the complex of mechanical properties of modern foreign high-strength steels can be significantly superior compared to traditional domestically produced steels. A limiting factor for steels with higher strength is their increased susceptibility to defect formation resulting from welding. Therefore, a fundamental aspect of developing welding technology for these materials is understanding how the metal properties change during the welding process and identifying the main microstructural characteristics that explain these changes.

It is generally known that the mechanical properties of metallic materials correlate with microstructural dimensions, most commonly with the average grain size, according to the Hall–Petch relationship [1, 2]:

$$\sigma = \sigma_0 + kd^{1/2},$$

where σ_0 is the lattice friction stress required to move individual dislocations; k is a material-dependent constant known as the slope of the Hall–Petch curve; d is the average grain size. The Hall–Petch relationship applies to a wide variety of materials and their properties, such as hardness, stress-strain state properties, and endurance limit [3, 4]. However, in addition to the average grain size, for weld metal characterized by stochastic grain orientation, it is necessary to consider other specific factors, such as differences in the orientation of ferrite plates within the body of structural grains, in order to predict material properties in the general case.

It is known that the strength and toughness of most steels at low temperatures can be improved through grain refinement during a controlled thermomechanical process. Numerous studies have shown that under the influence of thermal cycles, due to the peculiarities of metal crystallization process, anisotropy of structural and mechanical properties of the metal may occur, particularly low-temperature toughness, which may impose certain limitations on the selection of technological parameters for its processing [5–7]. Most studies on HSLA steels concern the microstructural characteristics and mechanical properties of the metal [8, 9], whereas the relationship between structural grain size, their orientation, and fracture toughness is still far from being understood due to the complex ferritic-bainitic-martensitic microstructure and the absence of a macroscopic numerical value that reflects this relationship.

Due to the fact that HSLA steels have an increased susceptibility to brittle fracture, the design of their welding technology requires the development of specific mechanisms that suppress crack formation and growth. Although microscopic defects, such as initial crack nuclei, are always present in weld metal, particular attention must be paid to mechanisms that help prevent their formation and branching, arrest their propagation, or even close cracks that are capable of growing or have already begun to grow. A fundamental review [10] demonstrates (Figure 1) that for HSLA steels, internal interfaces represent a relatively weak link with respect to crack formation and growth. This is related to the fact that elementary crack growth occurs through delamination and dislocation emission at the crack tip, that is, through decohesion of atomic bonds and the material's ability to create a zone of plastic relaxation around the propagating crack tip. Due to lower lattice coherency in grain boundary zones compared to their interior, cracks in high-strength steels can often propagate more easily along grain boundaries than through their interior.

Plastic slip at intergranular boundaries is determined by the competition between three microforces at the interface: the volume-induced microforce associated with bulk densities; the dissipative microforce associated with resistance to slip at the interface; and the energetic microforce associated with the Burgers vector of the network, which tends to counteract the accumulation of residual defects at the interface. Greater misorientation of adjacent grains retards normal slip at the interface and reduces the slip rate, increasing the strain hardening rate. At smaller grain sizes, larger deformation gradients develop, leading to the initiation of slip at the interface at lower shear strain.

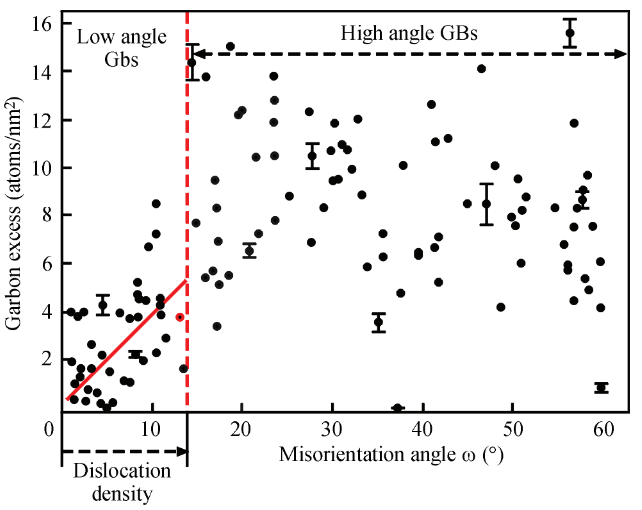

Figure 1. Schematic method for quantitative assessment of carbon segregation in ferrite [10]

The current viewpoint of some researchers is that the structural units that affect the toughness of ferritic-bainitic steels are grains with misorientation angles at grain boundaries greater than 15°. This is related to the fact that high-angle grain boundaries (HAGBs) with grain boundary misorientation angles greater than 15° are effective grains that contribute to crack arrest or its deflection at a large angle upon encountering an intergranular boundary during crack propagation [11, 12]. For BCC metals, a cleavage crack always propagates along {100} cleavage planes. The angles between adjacent grains will affect the ability to change the crack propagation direction, which is confirmed by the nature of fracture facets. For example, the authors of [13, 14] found that structural blocks with low grain boundary misorientation angles less than 15° (LAGBs) are microstructural units that control cleavage fracture and the increase in ductile-to-brittle transition temperature.

Direct studies of the effect of grain boundary misorientation on hydrogen transport, the results of which are presented in [15], showed that grain boundaries are pathways with high flux of dislocations and associated hydrogen, where the flux magnitude typically increases with increasing trap binding energy at grain boundaries. Modeling of hydrogen penetration in the early stages of deformation showed (Figure 2) that high-angle grain boundaries are faster pathways than low-angle ones.

It should be noted that currently, the volume of experimental data is insufficient to establish a relationship between toughness and structure in different directions of acicular ferritic-bainitic steels through analysis of {100} cleavage plane angles.

A large number of experiments show that cracks can propagate both directly through structural grains and through grain boundaries. Therefore, the effective grain size *d* according to the Hall–Petch relationship requires certain refinements with respect to ferritic-bainitic structures of HSLA steels. According to Professor Derek Raabe and colleagues from the Max Planck Institute in Düsseldorf [16], proper understanding and quantitative characterization of various interrelated effects of grain boundaries and associated effects are conditions for nanoscale engineering of damage-resistant HSLA steels.

In metallographic studies, the electron backscatter diffraction (EBSD) method is used as a criterion for characterizing grain boundaries to determine the overall misorientation angle of structural grains — an analytical method integrated with a scanning electron microscope. EBSD is a powerful microstructure characterization method that allows obtaining important information about grain orientation, phase identifica-

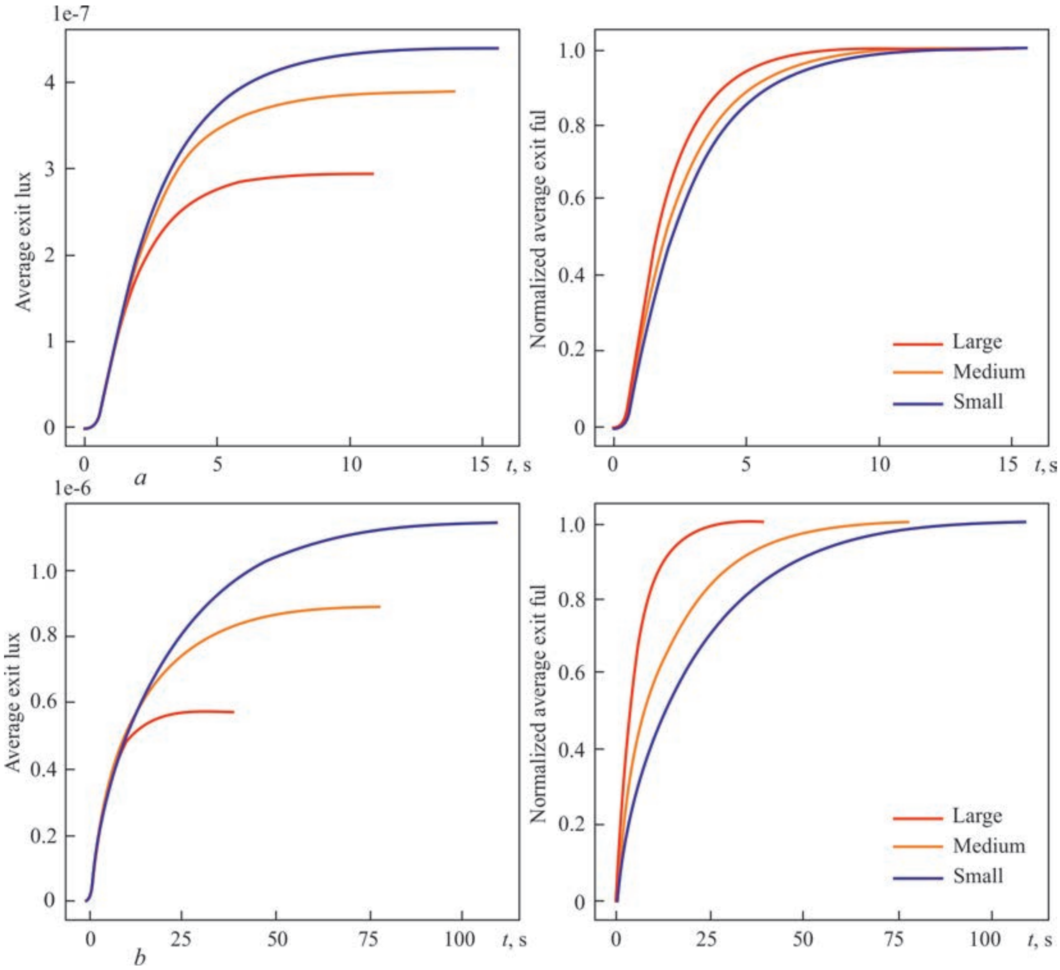

Figure 2. Curves of average and normalized output flux through low-angle (*a*) and high-angle (*b*) grain boundaries [15]

tion, and local deformation distribution. The method plays an increasingly important role in improving our understanding of material behavior. Modern computer programs for EBSD analysis allow processing of high-resolution images, enabling the analysis of fine-scale microstructures and obtaining detailed grain boundary characteristics. In addition, EBSD allows measurement of orientation gradients, which are necessary for understanding deformation mechanisms.

The EBSD method is widely used for characterizing the microstructure of martensitic and bainitic steels, allowing understanding of phase transformations and grain boundary characteristics. These capabilities are crucial for optimizing the mechanical properties of steels, such as strength, toughness, and ductility [17–20].

Reference [21] provides an example of automated identification and quantitative statistical analysis of bainite microstructural boundaries using EBSD data. The results indicate that crystallographic differences between different bainitic and martensitic structures provide a theoretical basis for understanding differ-

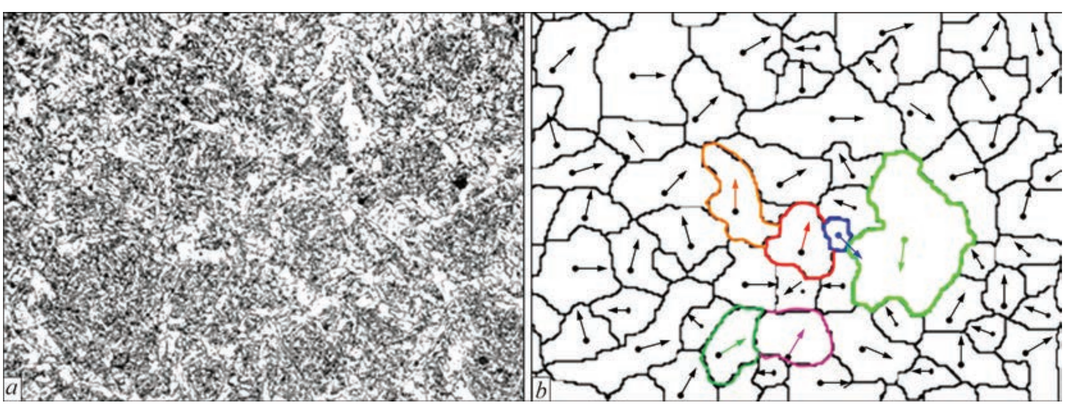

Figure 3. Microstructure of the base weld metal of 09G2S steel (×200) (*a*). Results of determining the principal orientation direction of structural grains and examples of misorientation of the principal vector of two adjacent grains at an angle not exceeding 15° (*b*)

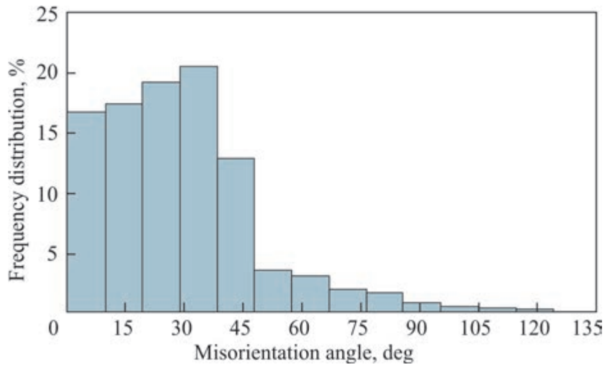

Figure 4. Distribution of misorientation angle at the boundary of two adjacent grains in the weld metal structure

ences in the mechanical properties of metal and allow high-throughput statistical analysis of these relationships. Another important aspect of EBSD is the determination of grain orientation angles in polycrystalline material, which define crystal orientation relative to the reference coordinate system. Determination of orientation angles allows obtaining a more accurate relationship between microstructural characteristics of the metal and its mechanical properties. Based on [21], EBSD can be effectively used for feature extraction and quantitative statistical analysis of microstructural information, and machine learning methods can become the foundation for establishing the relationship between microstructure and metal properties.

It should be noted that the EBSD method can be implemented on an electron microscope and requires installation of specialized software for processing Kikuchi patterns. As an alternative, a method based on Hough transformations can be considered, which allows detecting angular orientations of crystallographic planes in the microstructure. The Hough transformation calculation program is freely available, and in this case, the analysis is performed on images of metallographic structures obtained with optical microscopes. Such an approach can be used to determine not only the overall pattern of grain or crystal orientation angle distribution in the metal structure, but also at intergranular boundaries, which are among the most probable origines for brittle fracture nucleation. Exactly at these boundaries the possibility of crack transition from one grain to another or a change in its propagation direction is determined. According to this methodology, a computer program [22, 23] identifies each ferrite plate in the microstructure image, determines its area and the coordinates of the plane center, draws the maximum diagonal through the center, constructs a perpendicular to this diagonal, and determines the angle of its intersection with a specified axis (for example, the abscissa axis). Thus, each ferrite plate in the image is described by two parameters — ρ and θ (ρ is the distance from the origin to the line, and θ is the angle between the line perpendicular to the specified one and the positive direction of the abscissa axis). However, such an approach, considering the density distribution of ferrite plates in the grains of structural constituents of low-alloy steels, requires processing and analysis of a large volume of information. Modern computer analysis methods involving AI allow solving this problem.

An attempt to use the Hough transformation for metallographic studies of the weld metal microstructure of HSLA steel was described in [24]. The authors implemented a visual method for analyzing the orientation and misorientation of microstructural constituents using the Python programming language. Using AI, the position of the principal orientation vector of each structural grain was found (Figure 3) based on the Principal Component Analysis (PCA) method, which allows determining the main direction of grain orientation.

Based on this analysis, statistical data on grain misorientation angles were obtained (Figure 4), enabling analysis of the studied zone for the presence of such a critical parameter as the relative density distribution of LAGBs in the metal microstructure.

The permissible limits of grain misorientation in metallic structures depend on the specific material, its operating conditions, and manufacturing technology.

As can be seen from the data presented in Figure 4, approximately 20 % of boundaries between adjacent structural grains are characterized by a misorientation angle of no more than 35°. Such grain boundaries in-

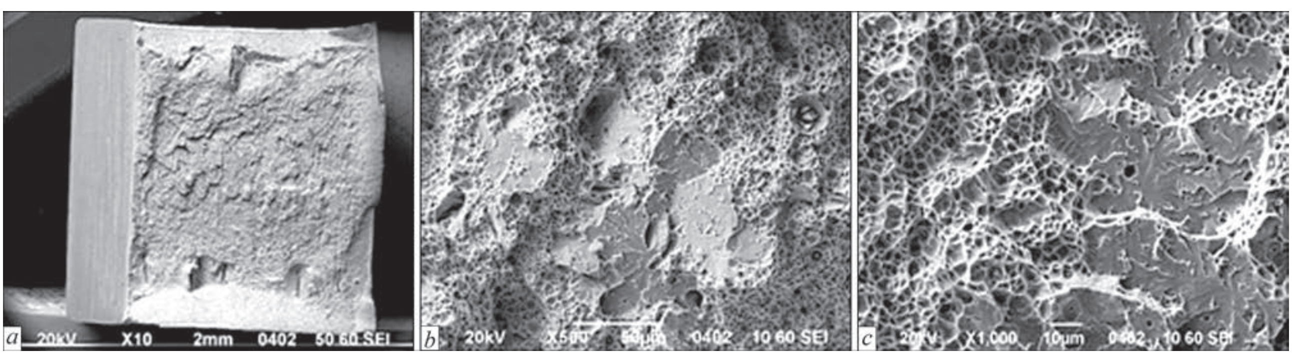

Figure 5. Fractographs of fracture surface of 09G2S steel weld metal specimen after impact bending test at a temperature of –20 °C

hibit crack propagation along grain boundaries and promote transcrystalline fracture. Figure 5 shows images of fractographs of a weld metal specimen fractured during impact bending tests at a temperature of –20 °C, which were obtained using a Jeol JSM35CF scanning electron microscope (Jeol, Japan). As can be seen from these images, the nature of crack propagation indicates precisely such a fracture process development — approximately one-third of cracks in this case have a transgranular nature.

Despite the agreement between the determination of misorientation angles at intergranular boundaries of the microstructure and the results of fractal analysis, such data are insufficient to establish a critical level of LAGB density in the metal microstructure as a "brittleness criterion". Such conclusions will only be possible after accumulating a substantial database of experimental data, their statistical processing, and through analysis. This should be the task of future research, the results of which will provide an opportunity not only to expand our knowledge base regarding the mechanisms of metal microstructure formation, but also to increase the level of mechanical properties of welded joints in HSLA steels.

CONCLUSIONS

A limiting factor in the adoption of modern high-strength low-alloy steels is their susceptibility to defect formation resulting from welding, which occurs during the welding process. Therefore, a fundamental aspect of developing their welding technology is understanding how metal properties change during the welding process and identifying the main microstructural characteristics that explain these changes.

When determining the influence of structural parameters on the properties of weld metal, it is necessary to consider such specific factors as differences in the orientation of ferrite precipitates within the body of structural grains.

The metallographic analysis method using Hough transformation, which can be implemented on optical microscopes, does not require specialized software on one hand, and allows determining the orientation of ferrite plates within the body of structural grains and, accordingly, the misorientation angle at the boundary of two contacting grains on the other hand, and should be considered as an alternative to the EBSD method.

Simplification of the procedure, through the use of AI tools, for determining structural grain orientation angles and misorientation angles at intergranular boundaries significantly increases the database of experimental data for establishing the critical level of LAGB density in metal microstructure as a "brittleness criterion".

The obtained results can be used in developing technological solutions when, in addition to structural grain size, attention is paid to forming a mixed microstructure with a balanced distribution of low-angle and high-angle grain boundaries, which will allow increasing both the strength and toughness of weld metal.

REFERENCES

1. Hall, E.O. (1951) The deformation and ageing of mild steel: III Discussion of results. *Proc. Phys. Soc. B*, 64(**9**), 747–753. DOI: http://doi.org/10.1088/0370-1301/64/9/303
2. Petch, N.J. (1953) The cleavage strength of polycrystals. *J. Iron Steel Inst*., **174**, 25–28.
3. Chapetti, M., Miyata, H., Tagawa, T. et al. (2004) Fatigue strength of ultra-fine grained steels. *Mater. Sci. Eng. A*, **381**, 331–336. DOI: https://doi.org/10.1016/j.msea.2004.04.055
4. Hansen, N. (2004) Hall–Petch relation and boundary strengthening. *Scr. Mater.,* **51**, 801–806. DOI: https://doi.org/10.1016/j.scriptamat.2004.06.002
5. Yang, X.L., Xu, Y.B., Tan, X.D., Wu, D. (2014) Influences of crystallography and delamination on anisotropy of Charpy impact toughness in API X100 pipeline steel. *Mater. Sci. Eng. A*, **607**, 53–62. DOI: https://doi.org/10.1016/j.msea.2014.03.121
6. Joo, M.S., Suh, D.-W., Bae, J.H., Bhadeshia, H.K.D.H. (2012) Toughness anisotropy in X70 and X80 pipeline steels. *Mater. Sci. Eng. A*, **556**, 601–606. DOI: http://dx.doi.org/10.1179/1743284713Y.0000000371
7. Jabr, H.M.A., Speer, J.G., Matlock, D.K. et al. (2013) Anisotropy of mechanical properties of API X70 spiral welded pipe steels. *Mater. Sci. Forum*, **753**, 538–541. DOI: http://dx.doi.org/10.4028/www.scientific.net/MSF.753.538
8. Sanchez, N., Petrov, R., Bae, J.H., Kim, K. (2010) Texture dependent mechanical anisotropy of X80 pipeline steel. *Adv. Eng. Mater*., **12**, 973–980. DOI: http://dx.doi.org/10.1002/adem.201000065
9. Cheng, S., Zhang, X., Zhang, J. et al. (2016) Effect of start cooling temperature on microstructure and properties of X80 pipeline steel. *Mater. Sci. Eng. A*, **666**, 156–164. DOI: https://doi.org/10.1016/j.msea.2016.04.066
10. Herbig, M., Raabe, D., Li, Y.J. et al. (2014) Atomic-scale quantification of grain boundary segregation in nanocrystalline material. *Physical Review Letters*, **112**, 126103. DOI: https://doi.org/10.1103/PhysRevLett.112.126103
11. Duan, Q., Yan, J., Zhu, G.H., Cai, Q.W. (2013) Effects of grain size and misorientation on anisotropy of X80 pipeline steel. *Hot Working Tech*., **24**, 107–109. https://caod.oriprobe.com/articles/41006381/Effects_of_Grain_Size_and_Misorientation_on_Anisot.htm
12. Masoumi, M., Silva, C.C., Abreu, H.F.G.D. (2018) Effect of rolling in the recrystallization temperature region associated with a post-heat treatment on the microstructure, crystal orientation, and mechanical properties of API 5L X70 pipeline steel. *J. Mater. Eng. Perfor*., **27**, 1694–1705. DOI: http://dx.doi.org/10.1590/1980-5373-mr-2016-0651
13. Deng, C.M., Li, Z.D., Sun, X.J., Yong, Q.L. (2014) Influence mechanism of high angle boundary on propagation of cleavage cracks in low martensite steel. *Mater. Mech. Eng*., **38**, 20–24.
14. Shen, J.C., Luo, Z.J., Yang, C.F., Zhang, Y.Q. (2014) Effective grain size affecting low temperature toughness in lath structure of HSLA steel. *J. Iron Steel Res. Int*., **26**(**7**), 70–76.
15. Hussein, A., Kim, B., Verbeken, K., Depover, T. (2024) The effect of grain boundary misorientation on hydrogen flux

using a phase-field based diffusion and trapping model. *Advanced Eng. Materials*, 26(**22)**, 2401561. DOI: https://doi.org/10.1002/adem.202401561
16. Raabe, D., Herbig, M., Sandlöbes, S. et al. (2014) Grain boundary segregation engineering in metallic alloys: A pathway to the design of interfaces. *Current Opinion in Solid State and Materials Sci.*, **18**, 253–261. DOI: https://doi.org/10.1016/j.cossms.2014.06.002
17. Stojanovic, N., Glisovic, J., Abdullah, O.I. et al. (2022) Particle formation due to brake wear, influence on the people health and measures for their reduction: A review. *Environ Sci. Pollut. Res.,* **29**, 9606–9625. DOI: https://doi.org/10.1007/s11356-021-17907-3
18. Vincentis, N.S., Roatta, A., Bolmaro, R.E., Signorelli, J.W. (2019) EBSD analysis of orientation gradients developed near grain boundaries. *Materials Research*, 22(**1**), e20180412. DOI: https://doi.org/10.1590/1980-5373-MR-2018-0412
19. Pauli, L., Heikki, R. (2022) EBSD characterisation of grain size distribution and grain sub-structures for ferritic steel weld metals. *Welding in the World*, **66**, 363–377. DOI: https://doi.org/10.1007/s40194-021-01225-w
20. Hwang, B., Kim, Y.G., Lee, S. et al. (2005) Effective grain size and Charpy impact properties of high-toughness X70 pipeline steels. *Metallurgical and Materials Transact. A*, **36**, 2107–2114. DOI: https://doi.org/10.1007/s11661-005-0331-9
21. Stojanovic, N., Belhocine, A., Abdullah, O.I., Grujic, I. (2023) The influence of the brake pad construction on noise formation, people's health and reduction measures. *Environ Sci. Pollut. Res.*, **30**, 15352–15363. DOI: https://doi.org/10.1007/s11356-022-23291-3
22. Li, X.C., Zhao, J.X., Cong, J.H. et al. (2021) Machine learning guided automatic recognition of crystal boundaries in bainitic/martensitic alloy and relationship between boundary types and ductile-to-brittle transition behavior. *J. Mater. Sci. Technol.,* **84**, 49–58. DOI: https://doi.org/10.1016/j.jmst.2020.12.024
23. Atiquzzaman, M. (1992) Multiresolution Hough transform an efficient method of detecting patterns in images. *IEEE Transact. on Pattern Analysis and Machine Intelligence*, 14(**11**), 1090–1095. DOI: https://doi.org/10.1109/34.166623
24. Zhuravel, I.M., Maksymovych, V.M. (2018) Quantitative analysis of orientation and elongation of grains on metallographic images using Hough transformations. *Naukovyi Visnyk NLTU Ukrainy*, 28(**5**), 135–139 [in Ukrainian]. DOI: https://doi.org/10.15421/40280528

ORCID
V.V. Holovko: 0000-0002-2117-0864,
O.O. Shtofel: 0000-0003-0965-6340,
D.Yu. Korolenko: 0009-0008-8582-5904

CONFLICT OF INTEREST
The Authors declare no conflict of interest

CORRESPONDING AUTHOR
V.V. Holovko
E.O. Paton Electric Welding Institute of the NASU
11 Kazymyr Malevych Str., 03150, Kyiv, Ukraine.
E-mail: v_golovko@ukr.net

SUGGESTED CITATION
V.V. Holovko, O.O. Shtofel, D.Yu. Korolenko (2025) Use of the Hough transformation method for the metallographic studies of ferritic-bainitic steels microstructure. *The Paton Welding J*., **11**, 35–40. DOI: https://doi.org/10.37434/tpwj2025.11.05

JOURNAL HOME PAGE
https://patonpublishinghouse.com/eng/journals/tpwj

Received: 21.02.2025
Received in revised form: 16.07.2025
Accepted: 18.11.2025