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Research Article

Fractal Analysis Method of Structural Components Orientation

[*a]Holovko, V., [b]Stofel, O. and [c]Korolenko, D.

[a-c]E.O. Paton Electric Welding Institute, Kazymyr Malevich, 11, Kyiv, 03150, Ukraine
Holovko, V. (ORCID ID 0000-0002-2117-0864); Stofel, O. (ORCID ID 0000-0003-0965-6340); Korolenko, D. (ORCID ID 0009-0008-8582-5904)
*Corresponding Author Email: vicholow@gmail.com

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Abstract
The experience of low-alloy high-strength steels using has shown that, along with significant advantages, they have a number of disadvantages. One of the most dangerous is considered to be the increased weld metals susceptibility to brittle fracture under the thermal cycle of welding, increased hydrogen content in the weld metal and a number of other factors influence. Efforts aimed at suppressing such a tendency are primarily associated with the dispersed microstructure formation with an intergranular boundary branched network, a reduced residual stress level. In addition to the above characteristics, toughness and plasticity levels are affected by the grains orientation in the metal microstructure. To determine this indicator, the electron backscatter diffraction (EBSD) method is used. The paper presents the results of a study of the possibility of using an alternative method based on the Hough transform to determine the grains orientation and the misorientation angle at the boundary of two neighboring grains in the weld metal structure. The possibility of using the results obtained on the basis of Hough transformations to assess the weld metal susceptibility to brittle fracture is shown.
Keywords: Low-alloy Steel, Welding, Microstructure, Brittle Fracture, Hough Transformation.

Introduction

Low-alloy steels have found wide application in various industries due to the successful combination of such different indicators as strength, ductility and toughness. The use of low-alloy steels in the welded metal structures manufacture has revealed a significant problem-a weld joints increased susceptibility to brittle fracture, which is associated with the peculiarities of the weld metal structure formation. A large number of studies are devoted to the description of the low-alloy steels weld joints structure and microstructure, which highlight the role of the structural composition, morphology of structural grains, non-metallic inclusions, dislocation structure, etc. In addition to the listed ones, one of the parameters that characterize the weld metal susceptibility to brittle fracture is the structure grains average orientation. In the weld metal, metal grains, unlike rolled steel, have a stochastic orientation, therefore, quantitative assessment of grain orientation is an important aspect in solving many weld metal materials science problems.

The requirements for the development of objective analysis methods make it urgent to work on creating approaches that would allow automating metallographic analysis methods, including the material grains orientation. This has led to the need to develop new and adapt known technologies to solve the tasks.

The study of the grain orientation distribution in the metals structure is performed using the electron backscatter diffraction (EBSD) method. Metallographic images analysis of the low-alloy steels microstructure shows that the ferrite plates orientation in the grain body may not be uniform, and this affects the cracks in the metal nucleation and development processes peculiarities [1]. To analyze the ferrite plates distribution in the grain body, a technique based on Hough transformations [2, 3] can be used, where each object 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 given and positive direction of the abscissa axis). However, such an approach, taking into account the ferrite plates distribution density in the low-alloy steels structural components grains, is associated with painstaking work and requires processing and analysis of a large information amount. Modern computer analysis methods with the AI involvement allow to solve such a problem and simplify the determination processes of structural grains orientation, improve the metallic materials properties, optimizing their microstructure.

The mechanical properties of a metal are usually associated with the grain size in its structure. This approach is used in technological processes aimed at increasing the metal toughness by reducing the grain size in the ferritic-pearlitic steels structure, but in relation to ferritic-bainite and bainite-martensitic steels, such certain features in the nature were revealed influence due to their complex hierarchy in morphology and crystallography [4, 5].

The HSLA steels weld metal metallographic studies indicate that cracks that have originated in the structure can pass through several grains (Figure 1a), stop at the intergranular boundary (Figure 1b) or in the middle of the grain (Figure 1c). That is, to assess the grain characteristics influence on the metal mechanical properties where the size index in some cases coincides with the grains size that have an allotriomorphic ferrite rim, and in others it is necessary to use the certain grains block size. This cracks development nature is associated with the peculiarities of the bainite polycrystalline structure formation in the weld metal.

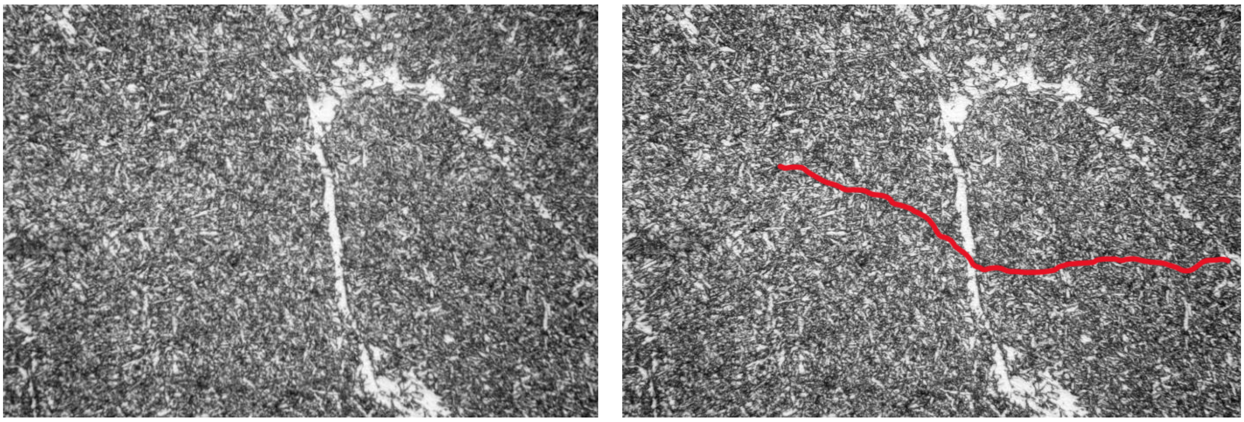

Figure 1a

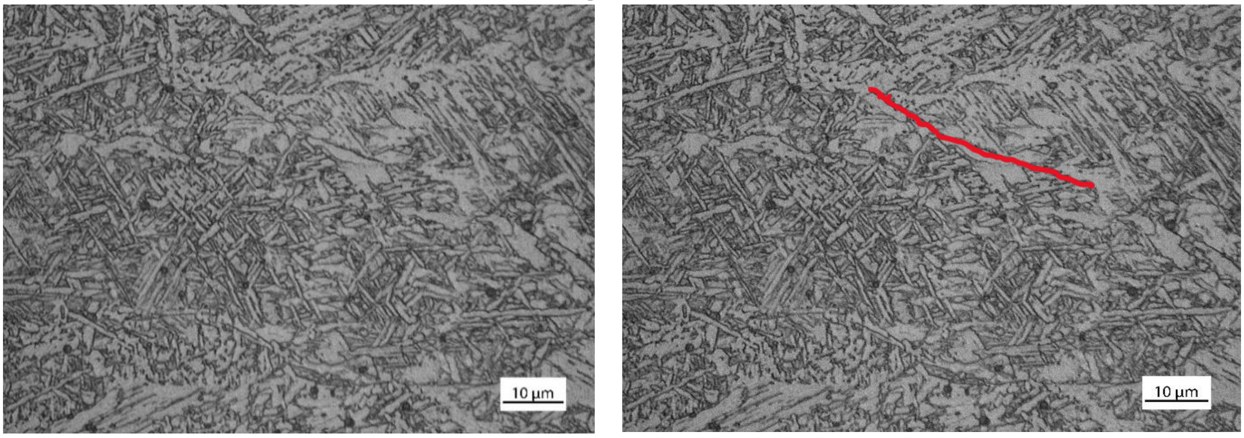

Figure 1b

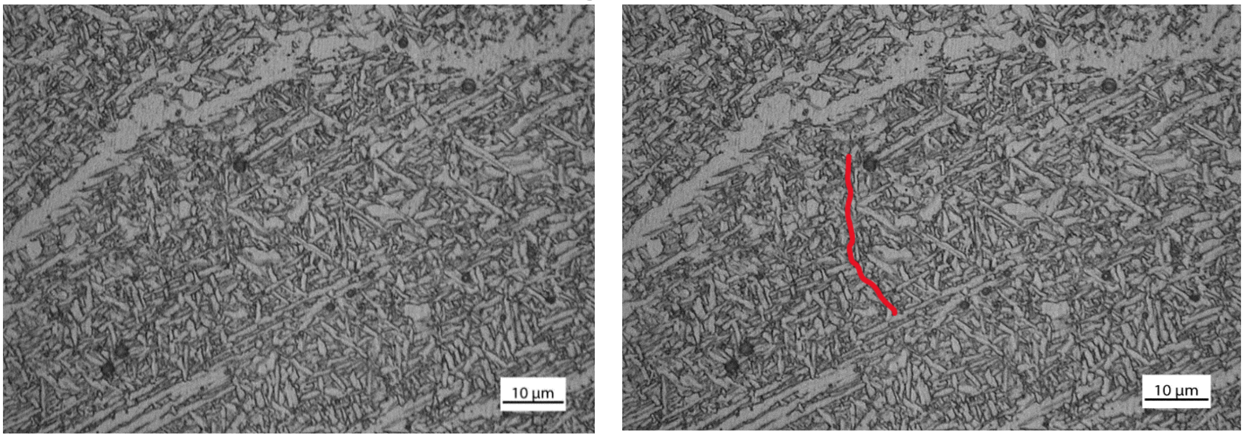

Figure 1c

Figure 1. Samples of the HSLA steel welds metal microstructure containing cracks: a) X200, b) and c) X1000.

Ferritic structures formed by bainite transformation are widely used in HSLA steels. The balance between the metal strength and toughness depends on the structural grains size, the dislocations density and fine cementite particles. The upper bainite structure consists of thin ferrite plates (less than 1 μm [7, 8]) based on a lath morphology [6]. The bainite structure usually consists of larger substructures [9, 10]-packets and blocks. A packet is a region containing ferrite plates with almost the same orientation direction, which are located close to each other. A block, which may appear to consist of a single grain, is a region consisting of ferrite plates with more individual plates within the range up to 15^0 pronounced crystallographic misorientation. The blocks and packages boundaries are mostly high-angle boundaries and are considered to hinder crack propagation. In metallographic studies, the total misorientation angle was proposed as a criterion for characterizing grain boundaries [11].

Today, there are different views among metallurgists on what can be considered high-angle grain boundaries (HAGB). Some researchers believe that HAGB should be greater than 15° [12, 13], while others believe that only HAGB greater than 40° [14] or 45° [15, 16] can significantly affect the strength of steels. In fact, the HAGB criterion is too general to reflect the polycrystalline structure crystallographic features.

Despite the fact that most HSLA steel welds metallographic studies are devoted to the microstructural characteristics study and their influence on the weld metal mechanical properties, the relationship between the structural grains size, their crystallographic orientation and fracture toughness is still far from being understood due to the complex metal polycrystalline structure. The current point of some researchers view is that the structural units that determine the metal toughness are grains with grain boundary misorientation angles greater than 15^0, however, a large number of experiments show that cracks can also pass directly through the HAGB (as shown in Figure 1). Thus, the effectiveness of using the traditional grain size parameter has significant limitations in relation to ferritic-bainite and bainite-martensitic steels.

To describe the polycrystalline microstructure influence on the metal mechanical properties, a certain differentiation of the grains (or packets) type has been proposed [17]. "Crystallographic" grains and/or packets (referred to as "crystallographic packets") correspond to grains or neighboring units sets that have the same crystallographic orientation. "Morphological" grains and/or packets (referred to as "morphological packets") are defined as parallel units bundles that can be observed in a light or scanning electron microscope after appropriate metallographic preparation. In metallographic studies, the crystallographic packet size is determined by EBSD, while morphological packets are studied by light microscopy after an etching.

Bainite is a microstructure consisting of parallel plates packets in a so-called morphological packet. The good toughness of this microstructure is due to the high-angle boundaries density that these microstructures typically have. Such boundaries act as barriers to crack propagation, forcing the crack to change its microscopic propagation plane to adapt to the new local crystallography. Low-angle boundaries are not effective barriers and therefore have no effect on the steels toughness. Therefore, from a fracture mechanics perspective, it is convenient to use the concept of an effective crystallographic packet, defined as a continuous ferrite plates set with crystallographic misorientation below a certain angle (here 15°).

Since the body-centered cubic metals the {100} crystal plane bond strength is lower than that of other crystal planes, the fracture crack preferentially propagates along the {100} crystal plane. As a result, more energy is required for the crack to cross grain boundaries with {100} cleavage plane angles of neighboring grains greater than 35° compared to angles less than 35°. The authors of [18] showed that a cleavage block consisting of grains with {100} cleavage plane angles less than 35° between grain boundaries is an effective grain for spallation failure.

The paper presents studies on determining the distribution of the ferrite plates orientation in the structural grains body of the low-alloy high-strength steels welds metal using fractal analysis methods.

Materials and Methods of Research

The research was conducted on low-alloy steel weld metal samples. The weld metal chemical composition and mechanical properties are given in Tables 1 and 2, respectively.

Sections for metallographic analysis were taken from the last pass of a multi-pass butt joint of metal 20 mm thick assembled for welding in accordance with the requirements of the ISO14171 standard (Figure 2). Welding was performed with a flux cored wire under a flux layer with an input energy of 14 kJ/cm.

Metallographic studies were performed on a Neophot 32 microscope equipped with a device for automatic image capture. The microstructure composition and its grain sizes were determined on structure optical images in the of the weld metal last pass center, which were obtained at a 2 mm distance from the weld surface with a X200 magnification and X500. Quantitative the microstructural components determination was carried out in accordance with the ASTME112-12 method. Photographs of microstructure samples are shown in Figure 3, and the microstructural components fraction is in Table 3. For further studies, optical images of the microstructure were subjected to fractal analysis. For this purpose, the images underwent a process of image binarization and cleaning from "noise".

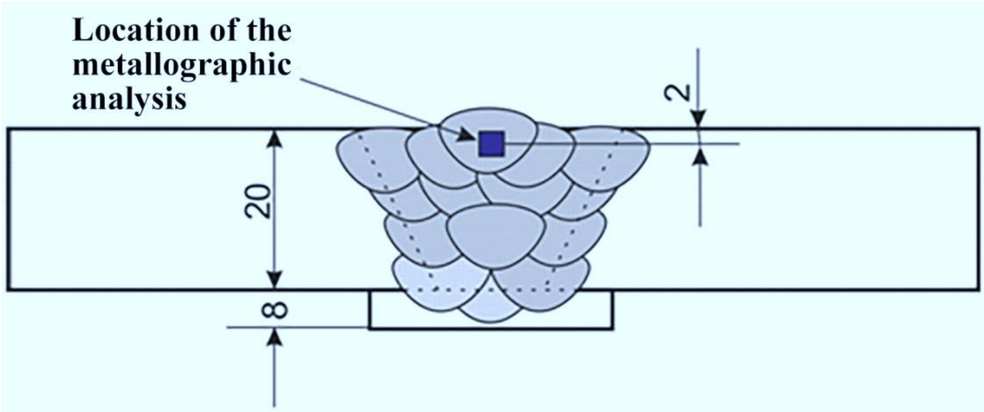

Figure 2. Scheme of the weld metal cross-section and the location of metallographic studies.

Table 1. Chemical composition of weld metal.

C	Si	Mn	S	P	Cr	Ni	Mo	Cu	Al	Ti
0,035	0,405	1,24	0,016	0,021	0,111	1,97	0,275	0,676	0,031	0,017

Table 2. Mechanical properties of weld metal.

σ_B	$\sigma_{0,2}$	δ	ψ	KCV, J/cm^2 at T, ^{0}C				
MПa		%		+ 20	0	– 20	– 40	– 60
709	636	19	57	85	72	60	50	32

Table 3. Content (vol. %) of the structure morphological forms and of ferrite grains size (d_f) in the weld metal microstructure.

Ferrite					Bainite		d_f, mm
AF	PF	IGF	GF	WF	UB	LB	
5	5	0	0	32	43	10	35-55
Note: AF–acicular ferrite; PF–polygonal ferrite; IGF–intragranular ferrite; GF–globular ferrite; WF–Widmanstett ferrite, UB–upper bainite, LB–low bainite.							

The orientation angle of the weld metal structural grains was determined on microstructure optical images, which were obtained on a Neophot 32 light microscope with a magnification of X1000. To determine the structure parameters, the MIPAR image analysis program (USA) v.4.2.1 was used. The MIPAR program uses deep learning technology using artificial intelligence (AI), which allows the software to be taught to adapt to the obtained microphotographs analysis, which are characterized by different contrast, brightness, structural elements size and texture features, as well as the technique of preparing samples for research.

The MIPAR program (above v.4.2) latest versions use a large procedures (recipes) library for determining grain sizes, volume fraction and size distribution of phases and inclusions, determining the orientation and structure inhomogeneity, the features of its texture, etc. The work used standard MIPAR program procedures (recipes) for determining the size and branching of grain boundaries in low-alloy steels.

Research Results

Metallographic studies were carried out on the last pass of the weld metal sample (Figure 2). The microstructure image sample obtained on a Neophot 32 optical microscope is shown in Figure 3a. In order to more clearly identify the structural grains boundaries, optical images of the structure were processed using the MIPAR (USA) v.4.2.1 image analysis program (Figure 3b). Further processing of the obtained images was performed using a program developed on the Hough transformations basis using the technique given in [2], which allows you to form a grain contour, determine this contour conditional center, draw the longest possible axis for each contour, construct a perpendicular to this axis at the conditional center point and determine the angle between this perpendicular and a predetermined direction. The perpendicular to the weld metals longitudinal axis was chosen as the predetermined direction. The structural grains orientation angle distribution is shown in Figure 3c.

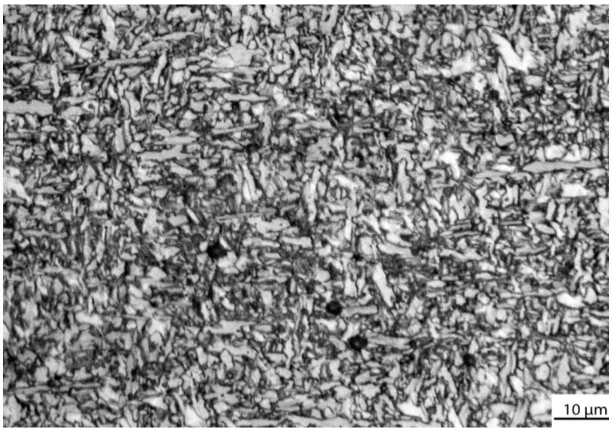

Figure 3a

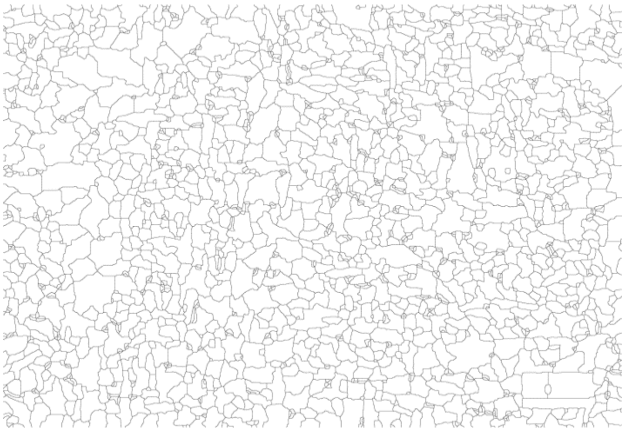

Figure 3b

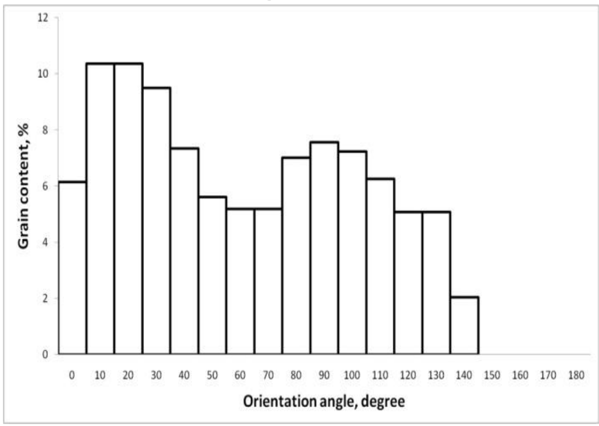

Figure 3c

Figure 3. Research results: a–the weld metal microstructure optical image; b–results of image processing using the MIPAR v.4.2.1 program; c–distribution of the structural grains orientation angle.

The results presented in numerical form allow for a certain analysis. It is known that the welds metal structure formation begins with the dendrites formation at the liquid metal bath contact line with the base metal melted grains. The dendritic structure growth occurs along the maximum temperature gradient direction, which at the beginning of crystallization is perpendicular to the welding longitudinal axis. The secondary structure formed in the further crystallization and recrystallization process has a largely stochastic orientation. As can be seen from the data shown in Figure 3c, most of the structural grains have an orientation in the range from 10^0 to 40^0, which confirms this trend.

Grain boundaries are central to plastic deformation and fracture in metals and alloys. Traditionally, only the average grain size is considered, according to the well-known Hall-Petch expression, together with the grain shape or texture, but the grain boundaries geometry and their composition play at least as important a role, and in some cases, dominate the grain size influence [19]. One of the parameters that plays a significant role in the crack propagation nature in low-alloy steels is the grain boundaries misorientation.

Grain misorientation in metallic structures is a phenomenon associated with a change in their spatial orientation as a result of mechanical, thermal or other processing. It can significantly affect the material mechanical properties. Grain misorientation in the welds metal occurs due to factors such as plastic deformation under the residual stresses influence, thermal cycling of the welding process, alloying or microalloying. The size of misorientation angle between two structural grains that have a common boundary can affect the nature of the cracks movement in the structure, as well as such the metal mechanical properties as plasticity and strength.

Usually, the structural grains orientation is conventionally divided into two categories: low-angle and high-angle.

Low-angle grain boundaries (LAB) (<15°) consist a dislocations dense network rather than fully misoriented boundaries. Such boundaries are stronger than high-angle grain boundaries and are more resistant to crack propagation due to better atomic bonding and the ability to hinder the movement of dislocations along grain boundaries. Cracks tend to bypass low-angle boundaries rather than propagate along them, so LABs promote transcrystalline (through-the-grain) fracture.

High-angle grain boundaries (HABs) (>15°) form at boundaries with reduced atomic bonding. Due to the fewer atomic bonds and increased tendency for decohesion, such boundaries can promote intergranular fracture, in which cracks propagate along grain boundaries rather than through the interior of grains.

The modern research results [20, 21] based on the experience of works published over the past two decades indicate the prospects and implementation of a new technological approach called "grain boundary engineering" (GBE). According to this approach, it becomes possible to find out to what extent the polycrystalline and functional materials structural bulk properties are controlled by the microstructures grain boundary characteristics. Accordingly, there is a certain potential for manipulating grain boundary microstructures by selecting material processing parameters for modern materials from metals to ceramics. For the grain misorientation analysis, electron microscopy, X-ray diffraction and EBSD (electron backscatter) methods are usually used. In this work, a visual orientation method and misorientation analysis using the Python programming language was considered.

With the help of AI, each grains main orientation vector position was found (Figure 4) based on the method based on the principal components analysis (PCA), which allows determining the grain orientation main direction.

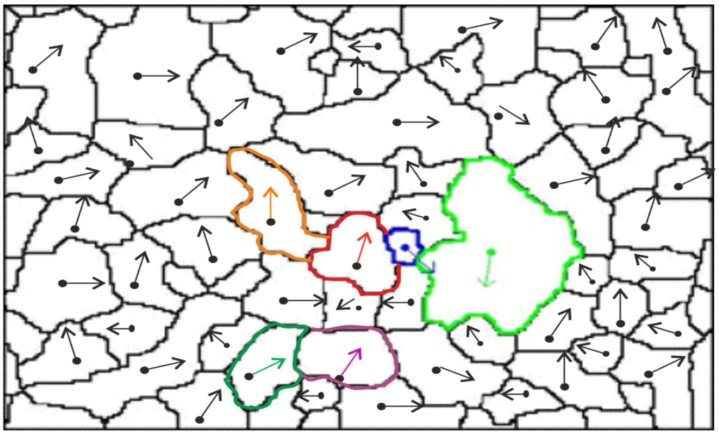

Figure 4. Examples of misorientation of the main vector of two neighboring grains by an angle of no more than 15^0.

Based on this analysis, statistical data on grain misorientation were obtained (Figure 5), which further allows analyzing the studied zone for the critical parameters presence.

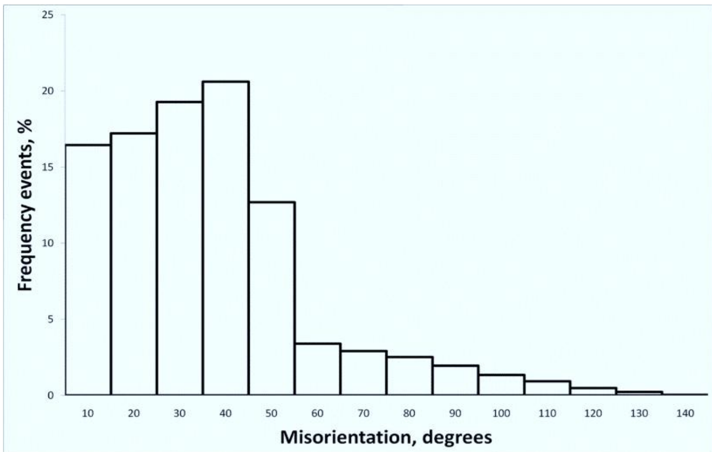

Figure 5. Distribution of the misorientation angle at the boundary of two adjacent grains in the weld metal structure.

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

As can be seen from the data presented in Figure 5, about 35% of structural grains are characterized by no more than 20^0 an orientation angle. Such grain boundaries prevent the cracks propagation along grain boundaries, but contribute to transcrystalline fracture. Figure 6 shows fractograms images of a sample destroyed during an impact test at a minus 20^0C temperature, which were obtained on an electron microscope JSM35CF. As can be seen from these images, the nature of the cracks development indicates precisely this fracture process development–the cracks in the metal in this case have trans granular in nature.

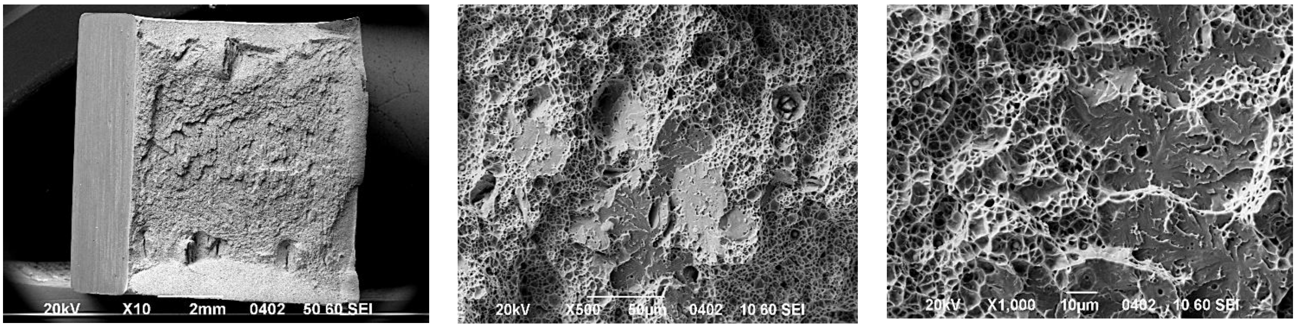

Figure 6a **Figure 6b** **Figure 6c**

Figure 6. Fractography of the weld metal sample fracture after the impact bending test at a -20^0C temperature.

It is advisable to conduct more extensive studies to determine the possibility of assessing the weld metal susceptibility to brittle fracture by parameterizing the misorientation angle at the grain boundary. The results obtained should contribute to the technological solutions development, when in addition to the structural grains size, attention is paid to a mixed microstructure formation with a LAB and HAB balanced distribution, which will allow increasing both the strength and toughness of the weld metal, forcing cracks to frequently change their trajectory, increasing the energy required for their propagation.

Conclusions

A study was conducted to determine the possibility the Hough transform using to obtain the metal structural components characteristics of low-alloy steels welds.

Work was carried out to create a method for the orientation and misorientation fractal analysis of the welds metal structural components. The developed model is based on the joint use of the Hough transform for processing metallographic images, the MIPAR image analysis program, and fractal analysis.

As a result of the metal structure images complex analysis, the model provides information on the metal structural grains misorientation angle in numerical form.

There is shown possibility of using data on the misorientation angle at the structural grains boundaries in numerical form to analyze the structural characteristics influence on the welds metal mechanical properties of low-alloy steels.

Declarations

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Author Contributions: HV: Definition of intellectual content, literature survey, prepared first draft of manuscript, implementation of study protocol, data collection, data analysis, manuscript preparation, and manuscript revision; SO: Concept, design, data collection, data analysis, manuscript preparation, and manuscript revision; KD: Review manuscript.

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