FRACTAL PARAMETRISATION OF THE WELD METAL MICROSTRUCTURE. Part 3

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Abstract

The growing of high-strength low-alloy steels use in the welded metal structures manufacture is accompanied by an increase in the requirements for the reliability of prediction results in the "composition-structure-properties" system. The fractal analysis methods use makes it possible to establish a metal structure characteristics numerical parameterization, the metallographic analysis of which gave only a qualitative assessment. The article shows the fractal analysis possibilities for the numerical evaluation of such of the structure of weld metal characteristics as the total length of grain boundaries, the distribution of dislocations at the grains structural boundaries, the distribution density of non-metallic inclusions accumulations with a distance less than 5r from one another. There was show the possibility of the structure and non-metallic inclusions numerical parameterization in the "structure-fractal-properties" system for predicting the mechanical properties of the low-alloy high-strength steels weld metal

Keywords: low-alloy steel; metallographic; fractal analysis; metal structure; non-metallic inclusions; mechanical properties.

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INTRODUCTION

The problem of assessing the structure and metal objects qualitative characteristics has been solved for a considerable period of time by the solid state physics methods and means, mechanics, chemistry, materials science, and other scientific disciplines. The reason for this is that the structure and the evaluation analysis of the metals qualitative characteristics is a time-consuming process and requires a complex approach, which consists in combining traditional evaluating methods the qualitative metals characteristics with new of their structural components evaluating methods. The traditional analysis methods such as electron and optical microscopy, X-ray structural analysis, quantitative metallography shows that none of them can be universal and suitable for solving the full tasks range of identifying the metal quality characteristics by analyzing its structure.

The metal structure usually consists of several factors, including the structural grains size, their boundaries branching, dislocations density, non-metals content, size and their distribution in the solid solution, and others. There is a large studies number on the each of these parameters influence on the metal mechanical properties. The metal ability to perform certain service functions does not depend on its structure individual indicators, but on the structure as a complete object. Such an assessment requires a statistical description of a heterogeneous data large volume. For this purpose, it is appropriate to use the fractal analysis method along with other diagnosis methods and welded metal structures quality control, metal structures components, parts, etc. The advantages of this method are low cost, speed of calculations and availability. One of the general issues remains the statistical data collection for various steels, alloys, metals, etc.

The possibility proof of using the fractal analysis method for the metal structure analysis is based on the comparison of the crystallization process with the geometric and stochastic fractals formation. From the definition of the term "fractal", it follows that a fractal is a figure that has the following properties: it has a complex structure at any magnification; is approximately self-similar; has a fractional Hausdorff (fractal) dimension, which is more topological; and can be constructed by recursive procedures.

To analyze the structural properties by the fractal method, it is necessary to analyze the crystallization scheme under one or another regime. From the typical microstructure example of the low-alloy steel weld metal, which is shown in Fig. 1, it can be seen that its components are various morphology ferrite grains (from acircular to globular), the second phase grains, non-metallic inclusions (up to 5 μm in size), cementite segregation.

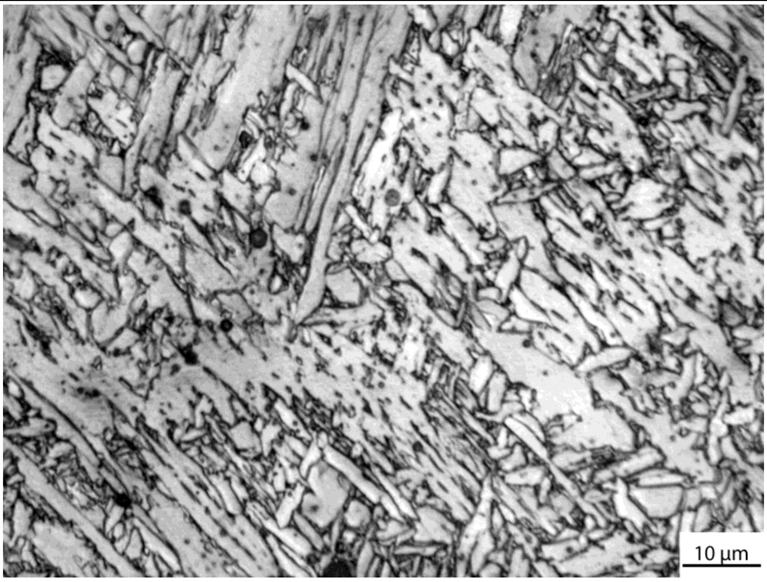


Fig.1. Typical microstructure of low-alloy steel weld metal

At first glance, the structure in Fig. 1 seems chaotic, however, if we consider the content and nature of each component distribution separately, it is possible to establish a certain order. To describe chaos, it is advisable to use synergistic approaches, which allow you to focus on phenomena that arise due to the joint several factors action, each of which does not lead to this phenomenon separately. In our work, self-organized zones/objects are considered in fig. 1, are different morphology crystals and non-metallic inclusions, which are the main factors in the manifestation of the sample necessary mechanical properties. Self-organization is understood as the involuntary, spontaneous self-complication of the structure, system, and its functioning laws as a slow and smooth changes result in its parameters. In other words, self-organization is the ordered structures formation from chaos.

The main fractals using purpose in the metallurgy field is to establish a connection in the system "structure - fractal/multifractal dimension — properties".

I MATERIALS AND METHOD

The research was carried out on weld metal samples, which were performed according to the method [1] during arc welding in shielding gas (82% Ar, 18% CO2) with flux-cored “metalcore” type wire with 1.6 mm diameter at a 200 (±5) A constant current, at an 30 (±2) V arc voltage with a 21 (±2) kJ/cm input energy. In order to form weld metal with a changed (within a certain range) structural components content, a powder wire with a 1.6 mm diameter was introduced into the "cold" part of the welding pool, The introduced wire core contained a mixture of 10% refractory compounds particles with a 0.040...0.200 mm size (inoculants) and 90% iron powder of the PZHV brand according to DSTU 9849. Titanium-based compounds were chosen as inoculants: titanium oxide (TiO_2 weld metal), titanium carbide (TiC weld metal), titanium nitride (TiN weld metal), as well as aluminum oxide (Al_2O_3 weld metal) and silicon carbide (SiC weld metal). The obtained results were compared with the data of weld metal samples obtained during flux-cored wire welding, the core of which included ferrotitanium (Base weld metal).

Metallographic studies were performed on transverse sections cut from welded joints. The welds metal structure was studied using a Neophot 32 optical microscope. Determination of the structural components content in weld metal was carried out according to the ISO 9042 method. The welds metal mechanical properties were evaluated according to the standard tests results in accordance with the DSTU ISO 6892-1:2019, DSTU EN 10045-1: 2006, DSTU ISO 15792 - 1: 2009 requirements. Photographs (optical images) of the structure and inclusions were studied using the fractal analysis method.

II. RESULTS AND DISCUSSION

The base metal (BM) chemical composition, the Base weld metal and welds metal with inoculants are given in Table 1. The welds metal mechanical properties are given in the table. 2.

The purpose of the study was to establish the possibilities of describing the weld metal structure as a whole object using the multifractal indiex. A multifractal is a complex fractal, which in turn consists of individual structural objects (Table 1) fractals: bainite grains, grain boundaries; non-metallic inclusions and others,

Table 1.

Chemical composition of the base metal and the metal othe examined seams

Weld №	C	Si	Mn	S	P	Ni	Mo	Al	Ti	Inoculant
BM	0.088	0.680	1.57	0.012	0.010	0.13	0.08	0.015	0.004	
Base	0,049	0,298	1,39	0,023	0,015	2,26	0,25	0,039	0,008	–
TiC	0,054	0,263	1,28	0,025	0,011	2,22	0,26	0,035	0,009	TiC
TiN	0,035	0,317	1,40	0,019	0,009	2,29	0,26	0,036	0,011	TiN
SiC	0,066	0,270	0,92	0,018	0,014	1,92	0,23	0,031	0,005	SiC
TiO_2	0,035	0,405	1,24	0,016	0,011	1,97	0,27	0,031	0,027	TiO_2
Al_2O_3	0,034	0,324	1,12	0,017	0,013	2,15	0,29	0,032	0,015	Al_2O_3

Table 2

Results of mechanical tests of the metal of the studied seams

Weld №	σ_B	$\sigma_{0,2}$	δ	ψ	KCV, J/cm^2 at T, ^{0}C		
	MPa		%		+ 20	0	-20
Base	746	690	19	60	73	79	63
TiC	715	644	19	63	112	93	85
TiN	712	580	5	15	55	47	40
SiC	726	650	21	62	85	72	65
TiO_2	709	636	19	57	85	72	60
Al_2O_3	728	621	17	54	82	58	50

The main calculations were based on the fact that:

• Inclusions were considered as a certain factor of influence on the ferrite structure formation, on the one hand, and also as an effective center of cracks nucleation and development.

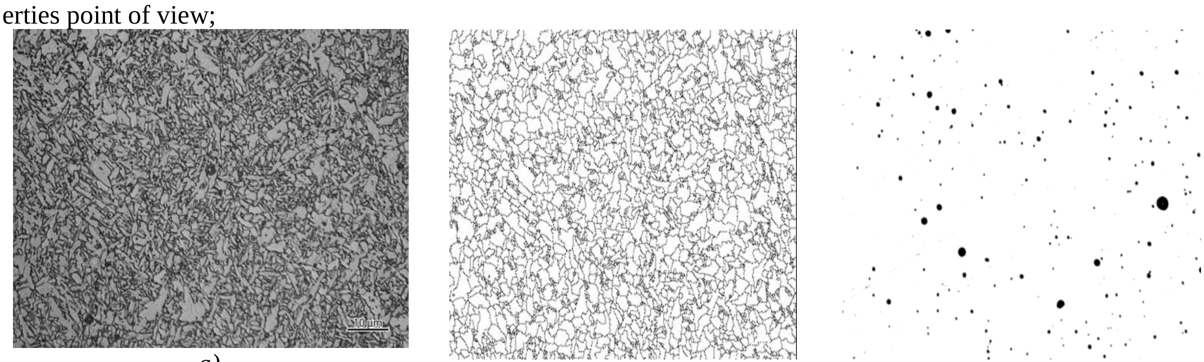
• Reducing the distance between two or more inclusions to less than five times the radius of the inclusion contributes to an increase in the stress level in the metal matrix near the inclusion;

• Bainite is a prominent structure component of of low-alloy steels welds metal from the mechanical properties point of view;

• The size of the structural grains and the grain boundaries branching have a direct effect on the weld metal strength and plasticity.

The influence of each microstructure constituent element on the weld metal mechanical properties can be described by the fractal dimension, and to generalize the microstructure influence, it is advisable to use a multifractal dependence.

The objects of the study were the weld metals microstructure grains, grain boundaries and non-metallic inclusions in a solid metal solution (Fig. 2).



а) б) в)

Fig. 2. Samples of research objects

Optical microscopy data showed that the weld metal secondary microstructure consists a bainite-martensitic mixture with a small ferrite component fraction (Fig. 1). The secondary structure composition and the structural grains size are given in Table 3. Bainite is represented by the morphological forms of upper, lower and intragranular bainite, ferrite by broken polygonal formations and Widmannstett ferrite outside the grains. Martensite is formed as a traditional acicular structure.

Table 3

The weld metal secondary structure composition

Weld №	The average share of components (%) in the weld metal microstructure				Size of structural grains, µm
	Lower bainite	Upper bainite	Martensite	Ferrite	
Base	50	30	10	10	54,30
TiN	30	57	10	3	51,23
SiC	30	50	10	10	41,89
TiO_2	25	45	10	10	41,17
Al_2O_3	15	50	15	15	45,24
TiC	25	60	10	5	44,18

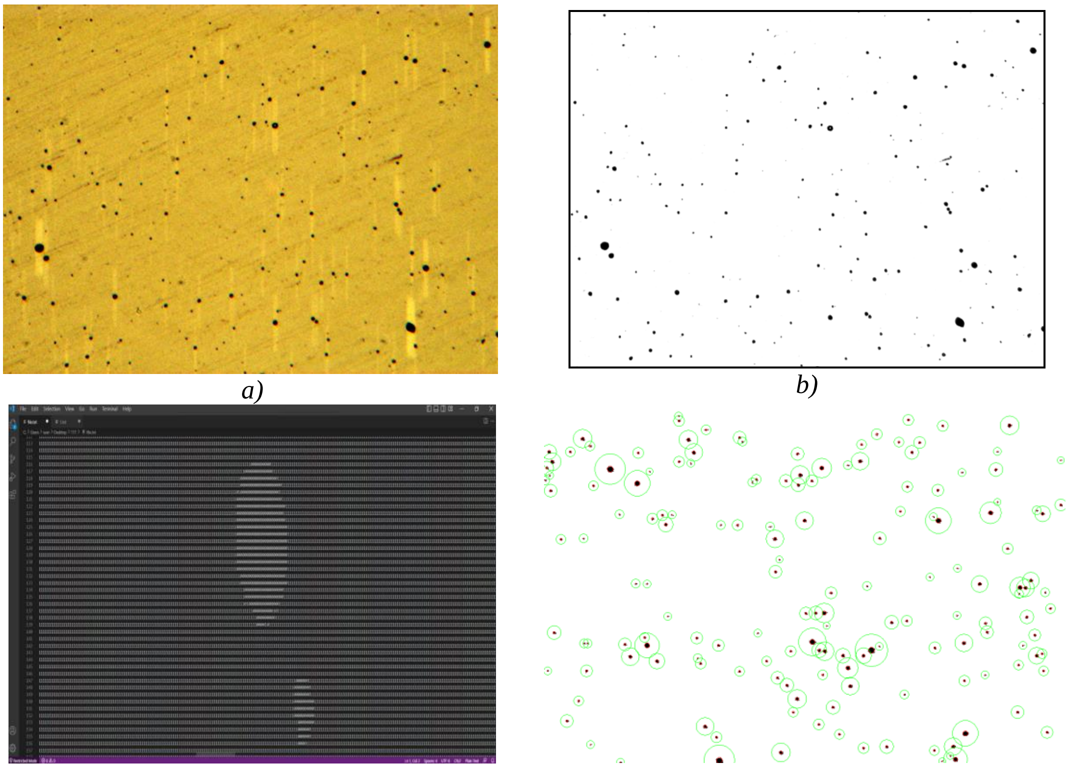
Fractal paramerization of the characteristics of non-metallic inclusions

The Minkowski method [2] was used to obtain the fractal dimension. For this purpose, several images were chosen for each sample. At the first stage, using the ImageJ program, the sizes of all structure grains and non-metallic inclusions were measured, the grain boundaries distribution and dislocations in the metal structure, as well as inclusions in the solid solution were studied (Fig. 3), and the fractal dimension of the studied objects was calculated using the Fractal program [3] objects.

For fractal analysis, five optical images of the secondary structure were selected at a X1000 magnification for each weld metal (Fig. 3a). After processing with the ImegeJ program, binary images of the corresponding structures were obtained (Fig. 3b), for which the fractal parameter was determined. The fractal parameterization results are given in Table 4.

The cellular method was used to calculate the fractal dimension. According to this method, the prepared fractal image (Fig. 1) is covered with grids with square cells ("box counting method)" with a decrease in the grid step d to 1px = 0.0377μm, and the number of cells N(d) in which the information boundary (the boundary grains) of the investigated fractal object - structure. The fractal image D dimension is determined as an approximation result of the obtained points set using the least squares method according to expression (1).

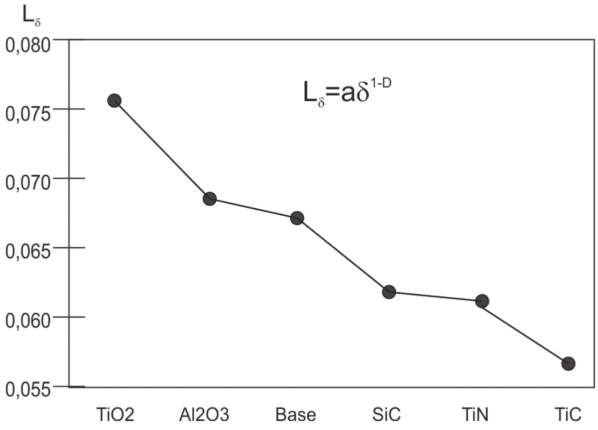
$$D = \lim_{d \to 0} \frac{\ln N(d)}{\ln \frac{1}{d}} \quad (1)$$



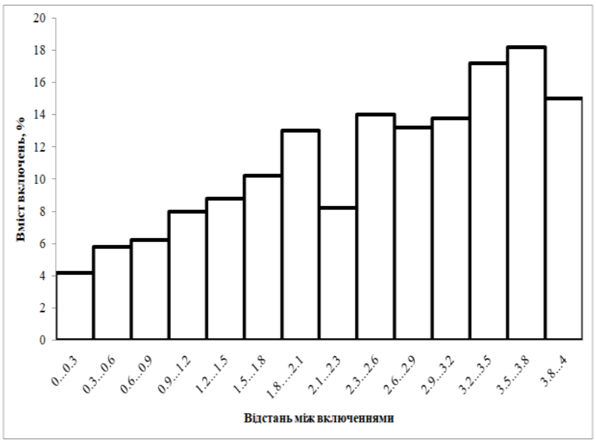
a) b) c) d)

Fig. 3. Cuts of weld metal samples: a) real photo; b) photo cleared of "garbage"; c) analysis of inclusions geometry; d) identification of inclusions and their surroundings.

During the research using the specified method, data were obtained on the branching parameter of non-metallic inclusions (Fig. 4a) and the density of their distribution at a distance of less than 0.5r from each other (Fig. 4b). It should be noted that the program component does not take into account the size of the inclusions, but only shows their clustering at 0 to 4 μm distance on each subsequent one.



a)



б)

Fig. 4. Analysis of the obtained data: a) branching of non-metallic inclusions, where L is a parameter that shows the total non-metallic inclusions length on the section, taking into account the obtained photo scale and the corresponding fractal dimension Dnm; b) distribution of inclusions over the section area, taking into account the maximum studied distance from each, as 5 radii of the largest inclusion being studied.

It is known that non-metallic inclusions with a size of 0.3 to 0.8 μm have the most noticeable effect on the low-alloy steels weld metal secondary microstructure formation. Fractal analysis methods make it possible to identify the influence of a certain inclusions group on the weld metal mechanical properties. This approach made it possible to consider the effectiveness of the inclusions content with a size of 0.3...0.8 microns at a weld metal determined impact viscosity.

One of the important inclusions characteristics is their distribution in the metal structure. Inclusions, which are located more or less uniformly in the structure, do not have a great influence on the metal mechanical properties. There may be inclusions in the weld metal, which are located at a distance from each other more than five times the inclusions radius ($L \geq 5r$), or in the form of clusters ($L \leq 5r$), or are located in the form of chains at the grain boundaries. In the last two cases, such clusters can be nucleation centers of brittle metal destruction. Unfortunately, modern metallographic studies methods do not take into account the of the inclusions distribution density in the metal matrix.

In order to assess the influence of non-metallic inclusions, using a fractal indicators method has been developed to describe the non-metallic inclusions content in the weld metal. The program [4] applies the algorithm of recursively traversing the pixels of the inclusion area in the image. Statistical and stereometric inclusions characteristics are calculated based on the assumption of the inclusions round shape. Thus, we estimate the inclusion radius as $\sqrt{S/\pi}$, where S is the area of the inclusion in pixels. After calculating the inclusions size, the program builds histograms of the inclusions distribution by area and size. The latter is used as a basis for calculating the Pearson test $\chi 2$ value, which is used to check whether the obtained sample belongs to one of the predefined distribution types.

Table. 4.

Fractal characteristics of structural components

Weld №	Vinc	Dnm	$D_{0,8}$	Dgz	Lgz	Dz	Ddis
TiN	0,77	0,928	1,009	1,9387	17078	2,2101	0,2309
Al_2O_3	0,37	0,962	1,067	1,8252	12949	2,1862	0,2956
TiO_2	0,47	1,025	1,119	1,8149	13174	2,1240	0,4975
SiC	0,64	0,940	1,102	1,9316	14226	2,1370	0,5303
Base	0,62	0,952	1,252	1,9069	16112	2,1740	0,4540
TiC	0,62	0,924	1,254	1,8765	13893	2,2326	0,5423

Notes: Vinc is the content (%) of non-metallic inclusions in the weld metal, Lgz is the total length of grain boundaries, Dnm D0.8, Dgz, Ddys, Dz are fractal parameters of non-metallic inclusions, inclusions clusters at a distance less than 5r from each other, grain boundaries branching, the dislocations distribution at grain boundaries, bainite grains, respectively, which were obtained as the analysis result of weld metal structure optical images.

The program also provides the ability to filter out noise in the image (for example, individual pixels that introduce a significant bias to the histograms when studying the inclusion sizes distributions and distances between them), and also allows users to create charts with different numbers of columns.

Fractal parameterization of the grain structure

In steels and alloys, the grain boundaries structure has a decisive influence on the mechanical properties set. With sufficiently the metal fast crystallization of the weld pool, in conditions far from equilibrium, a polycrystalline structure is usually formed in the welds metal, the grains of which, depending on the growth conditions, collision and recrystallization, have an arbitrary shape. The grains crystal lattice along the boundaries is under the lattices force fields influence of both touching crystallites, saturated with impurity atoms, dislocations, vacancies, and has a grain boundaries increased energy. These circumstances contribute to the fact that grain boundaries are the places of the highest nucleation probability and cracks development. The metal strength indicators are determined by the grains size in accordance with the Hall-Petch dependence, on the one hand, and the dislocation structure density at the grain boundaries, on the other, as well as the dispersion hardening influence, which depends on the distribution density in the metal structure of non-metallic inclusions clusters that are at a distance of less 5r from each other.

The structure grains effect on metal strength indicators can be described using the fractal parameter D_σ:

$$D_\sigma = D_g + d^{-0,5} \quad (3)$$

where the first component represents the branching contribution of the grain structure, and the second is the effect of grain sizes.

Fractal analysis methods make it possible to also take into account the dislocation structure influence on metal strength indicators using the D_{dis} indicator and non-metallic inclusions clusters using the $D_{0.8}$ indicator.

The multifractal indicator D_{mf} allows you to describe the total contribution of these three components:

$$D_{mf} = D_\sigma + D_{dis} + D_{0,8} \quad (4)$$

The results of determining the total indicators effect of the grain structure (D_σ), dislocation structure (D_{dis}) and dispersion strengthening ($D_{0.8}$) on the weld metal yield strength ($\sigma_{0.2}$) are presented in Fig. 5.

It should be noted that the program that was used in the research allows you to calculate the fractal parameter of the grain boundaries branching without taking into account their thickness, as well as the fractal parameter of the dislocations distribution at the grain boundaries, and this somewhat reduces the correspondence between the calculated data and the experimental results.

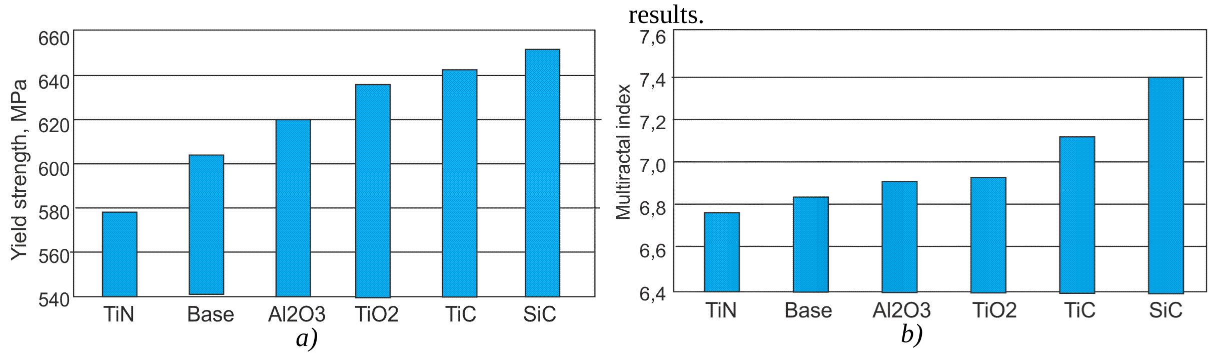


Fig. 5. The results of determining a) the welds metal yield strength and b) the multifractal indicator Dmf

Thus, the given system analysis example indicates the possibility of expanding the knowledge base regarding the structural components specifics effect and non-metallic inclusions in the metal structure on such welds mechanical properties as strength indicators, plasticity and viscosity due to the use of fractal analysis methods in the of metal structures for low-alloy high-strength of steel.

Establishing stable and reliable dependencies in the "composition-structure-properties" system in relation to the welding technology parameters prediction, the welding materials requires selection, are use for an expanded knowledge base on the structure formation and non-metallic inclusions features in weld metal, and their influence on the welded joints mechanical properties. Increasing the use of fractal parameterization methods to analyze the welds structure characteristics in the "structure-fractal-properties" system will contribute to the development of research in the metallurgy and welded metal structures fields.

Conclusions

A study was conducted using the fractal analysis methods of the structural grains and non-metallic inclusions effect on the low-alloy steels weld metal mechanical properties limits indicators.

As the conducted research result, it was established:

1. The use of fractal parameterization methods for the structure optical images analysis makes it possible to significantly expand the indicators scope of the metal structure and non-metallic inclusions involved in the "composition-structure-properties" dependence description.

2. The of fractal analysis methods make it possible to obtain the numerical parameterization of such structural grains parameters as the idealized ("pure") grain boundaries size (L_{gz}), the information grain boundary (D_{gz}) and the dislocation structure density at the grain boundaries (D_{dis}).

3. Fractal analysis of the optical images the non-metallic inclusions distribution in the metal matrix allows to obtain the inclusions content numerical parameters (D_{nm}) and the clusters of inclusions distribution density at a distance less than 5r from each other.

4. Involvement of fractal analysis in the digital of structure and non-metallic inclusions indicators parameterization in metal allows to significantly expand the information base used in modeling in the "composition-structure-properties" system, in relation to low-alloy steels welding.

References:

1 Holovko V.V., Yermolenko D.Yu., Stepanyuk S.M., Zhukov V.V. and Kostin V.A. (2020) Influence of introduction of refractory particles into welding pool on structure and properties of weld metal, The Paton Welding Journal, #8, p.1-7.

2 Sinha S., Kim D-I., Fleury E., Suwas S. 2015 Effect of grain boundary engineering on the microstructure and mechanical properties of copper containing austenitic steel Mater. Sci. Eng. A 626. p.175-185.

3 Zhang I., Lu C., Tieu K. 2016 A review on atomistic simulation of grain boundary behaviors in face-centered cubic metals Computer Mater. Sci. 118 180-191.

4 Krasikov I.V. et al. Computer program « Fraculator 2» .Certificate of copyright registration for the work No. 115438. Ukraine, 10/25/2022.