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APPLICATION OF FRACTAL AND METALLOGRAPHIC ANALYSES FOR EVALUATION OF QUALITY OF WELD METAL

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When analyzing the factors that determine the mechanical properties of welds, it is necessary to take into account both the size of individual components of the structure and their morphology. It is shown that the use of the method of fractal analysis makes it possible to numerically determine such parameters of weld metal microstructure, as the size of nonmetallic inclusions, and branching of grain boundaries, which was impossible at analysis of metallographic images. The results are obtained, which indicate the need to include in the multifractal analysis the characteristics that describe the morphological features of microstructural components, the distribution of nonmetallic inclusions by size, and the level of alloying of the solid solution. Research directions for the development of multifractal analysis of welded joints have been identified. 10 Ref., 2 Tables, 6 Figures.

Keywords: metal of welded joints, fractal and metallographic analyses, structural parameters, mechanical characteristics

The general objective of metallographic analysis is investigation of the structure and defects, in particular, such as inclusions, base metal and deposited metal of the welded joint. Metallographic analysis includes investigations of metal macro- and microstructure. This list was recently complemented by fractal analysis method [1]. In works [2–5] the authors describe the cause for application of fractal analysis method, based on fractal concepts known in different scientific fields. The main purpose of fractal application in the materials science field is establishing a connection in the «structure–composition–fractal/multifractal dimension–properties» system. The above-described approaches were used to describe in work [6] one of the stages of searching for connections between the results of fractal analysis and the data of the reference scale of structural components in the metal of low-alloy steel welds. Existence of «fractal dimension–grain size» and «fractal dimension–structural parameters» connections was shown.

This work describes application of fractal analysis method for analysis of the structure of weld metal samples. Metallographic investigation can be used to establish the parameters, which affect the metal quality, in particular, to reveal certain metal defects, presence of oxides on the grain boundaries, «contamination» by nonmetallic inclusions, size of metal grains, chemical composition of weld metal, presence of microscopic cracks, pores and other structural defects. In order to establish a connection between the structural composition of the metal and its mechanical properties, it is necessary to conduct quantitative description of the structural complex, i.e., perform its parametrization. At present, structure description in materials science is based on their approximate representation in the form of geometrical objects of certain dimensions. Here, parameters characterizing individual structural elements, and not the structure as a whole, are used. That is, the size of structural grains, blocks, and nonmetallic inclusions is assessed, but no answer is given on the influence of the sum of these characteristics on metal properties.

Metallographic analysis is one of the methods of welded joint testing. It is usually performed at final inspection of finished welded joints. The finished joint should completely meet the operation requirements. The total labour consumption of all the inspection operations is equal on average to 30 % of the total labour consumption of welded metal structure fabrication. Researchers know well that it is impossible to describe the impact of the structure on the mechanical properties of steel just on the base of determination of the geometrical features of the structure grains. Both the parameters of grain boundaries and of nonmetallic inclusions should be taken into account. Characteristics of grain structure, grain boundaries and nonmetallic inclusions can be combined in one analysis only using the methods of fractal parameterization and multifractal analysis of metal. In particular,

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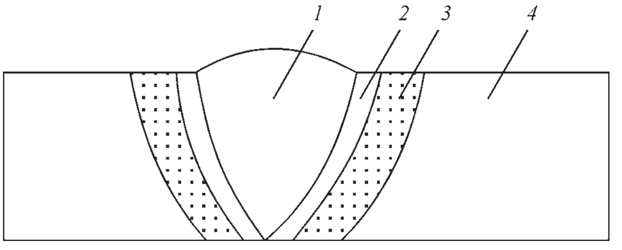

Figure 1. Scheme of weld metal structure: *1* — weld; *2* — fusion zone; *3* — heat-affected zone (HAZ); *4* — base metal

studies using fractal analysis of the influence of parameters of nonmetallic inclusions contained in the welds on the mechanical properties of the metal [7], allowed comparing the values of fractal dimension with the characteristics of destruction of weld metal structure [8].

The scheme of weld metal structure (Figure 1) consists of four main zones. The first zone is base metal (*4*), the structure of which was formed during rolled sheet production and was not exposed to thermal impact.

On the boundary of contact of weld pool molten metal (*2*) with the base metal an abrupt temperature gradient and overcooling phenomenon develop in a thin layer of metal along the fusion line that leads to formation of a large number of crystallization centers resulting in the fine-grained structure of the layer. Base metal zone (*3*), which was exposed to thermal impact from the weld pool and welding arc, is the columnar crystal zone. In the weld metal proper (*1*) the conditions of heat removal and degree of overcooling of steel change over time. As a result, the weld metal structure contains both columnar crystals and equiaxed crystals. The welded joint metal belongs to materials, exposed to energy impact during manufacture or treatment. Presence of connections between the elements in an open system, determines formation of a collective response to the external impact of the welding arc. As a result of such a reaction, a structure forms in the weld metal, which corresponds to a certain spatial, time or space-time self-organization that, in its turn, causes changes in the metal properties as a whole (Figure 2).

The structure of weld metal is traditionally described using the methods of optical and electron metallography. Such approaches are insufficient at description of systems with a complex and heterogeneous structure, which weld metal structures are, as they do not allow for one of the most important properties of the system — its integrity. One of the promising ways to solve the problem of quantitative description of material structures is their parameterization, based on application of fractal theory.

Investigations of the parameters of welded joint metal structure by fractal analysis method provide a certain set of data as regards the fractal dimension for zones *1*, *2*, *3* and *4*. These values add up to one general concept of a multifractal, which, in its turn, is an inhomogeneous fractal, and, therefore, each of the multifractal components has its own specific weight.

In order to study the connection between the fractal parameters of the structure and mechanical properties of weld metal, investigations were conducted on samples of the metal of welds on low-alloy high-strength steel. During the experiment, the metal impact toughness at different temperatures (from 20 to –40 °C) was studied on samples of welds, produced at welding of butt welded joints of 09G2 steel by Sv-08GNMA wire in M21 shielding gas atmosphere. During the experiments the impact of weld pool modification on weld metal structure and properties was studied. Weld pool modification was performed by a procedure, presented in work [9]. Results of spectral analysis of weld metal given in Table 1, are indicative of the fact that by its chemical composition the weld metal corresponds to steel strength category K60. Samples for metallographic investigation were cut out of welds from welded joint zones *1–4*, which are shown in Figure 1. At metallographic investigations parameters of nonmetallic inclusions and structural components were determined. Results of metallographic analysis of the samples in NEOPHOT-32 microscope at ×1000 and ×320 magnifications were recorded using a digital photocamera (Figure 3).

To confirm the stochasticity of fractal functions which describe the influence of the dimensions of structural components, images of the structure at dif-

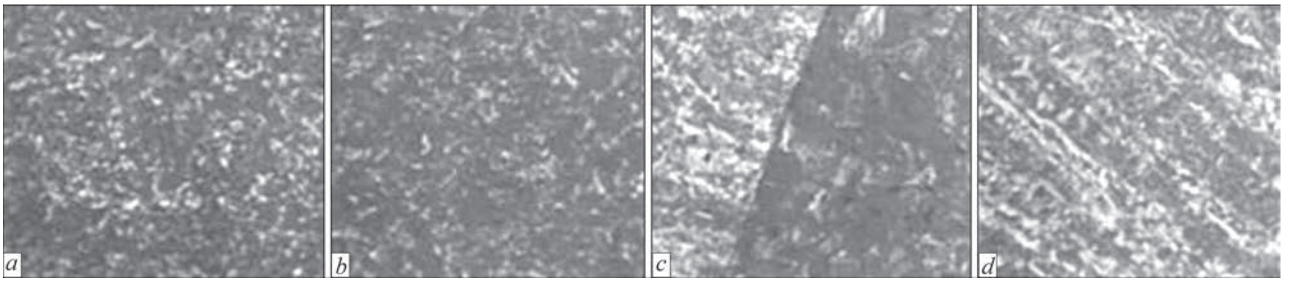

Figure 2. Scheme of the structure of low-alloy steel welded joint: *a* — base metal; *b* — overheated zone; *c* — on the fusion line; *d* — weld metal

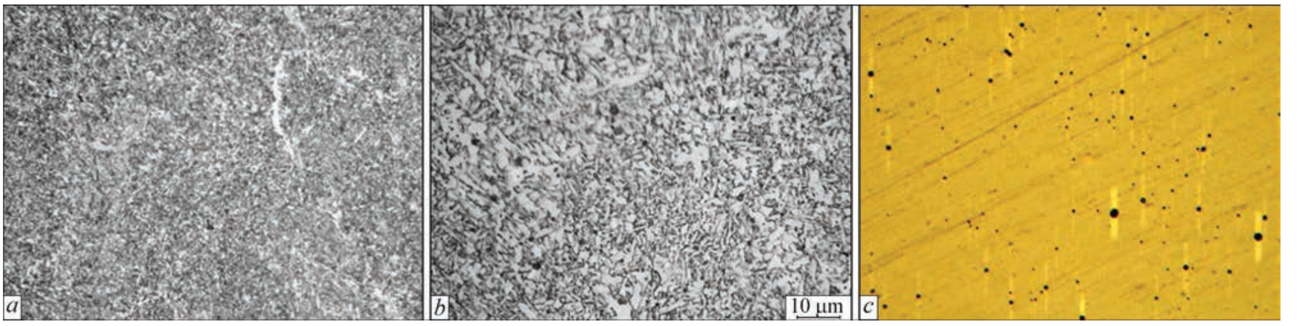

Figure 3. Typical microstructures of welds: *a* — ×320; *b* — ×1000; *c* — nonmetallic inclusions, ×1000

Table 1. Chemical composition of metal of the studied welds (deposited metal), wt.%

Weld number	C	Si	Mn	S	P	Cr	Ni	Mo	Al	Ti	Modifier
W1	0.054	0.263	1.28	0.025	0.011	0.13	2.22	0.26	0.035	0.009	TiC
W2	0.035	0.317	1.40	0.019	0.009	0.14	2.29	0.26	0.036	0.011	TiN
W3	0.066	0.270	0.92	0.016	0.024	0.14	1.72	0.23	0.021	0.005	SiC
W4	0.035	0.405	1.24	0.016	0.021	0.11	1.97	0.27	0.031	0.027	TiO_2
W5	0.034	0.324	1.12	0.017	0.023	0.12	2.15	0.29	0.032	0.025	Al_2O_3

Table 2. Results of mechanical testing of weld metal of the studied samples and results obtained by fractal analysis method

Weld number	D_{inc}	D_{320}	D_{1000}/D_{inc}	D_{1000}	*KCV*, J/cm² at *T*, °C			
					20	0	–20	–40
W1	0.928	1.902	0.488	1.877	112	93	85	73
W2	0.91	1.938	0.469	1.939	55	47	40	33
W3	0.907	1.941	0.467	1.932	85	72	65	61
W4	0.920	1.907	0.483	1.815	85	72	60	50
W5	0.919	1.897	0.485	1.825	82	58	50	36

ferent magnifications were used at assessment of the values of weld mechanical properties.

Fractal analysis of the structural components was performed on the base of a procedure, given in work [10]. Used as the data base were the results of digital processing of images, obtained at metallographic analysis of samples in NEOPHOT-32 optical microscope. Fractal index of nonmetallic inclusions in the weld metal in images with x1000 magnification (D_{inc}), as well as branching of grain boundaries at ×320 (D_{320}) and ×1000 (D_{1000}) magnification, were determined. In addition, Table 2 gives the results of determination of D_{1000}/D_{inc} ratio, as an example of multifractal analysis. Results of fractal analysis and impact toughness of weld metal at testing in the temperature range from 20 to –40 °C are given in Table 2.

From the data given in Table 2, the closeness of indices D_{320} and D_{1000} (less than 10 % difference) should be noted first of all that is indicative of the stochasticity of fractal dependence and possibility of its application for assessment of weld metal structure as a whole.

For visualization of the applicability of individual indices of fractal dimension (in the form of relative units) for assessment of the metal mechanical properties, graphs of interrelation of impact toughness and fractal dimension of the inclusions (Figure 4) and dependence of impact toughness and fractal dimension of grain boundaries in weld metal microstructure (Figure 5) were plotted by the results of impact toughness testing.

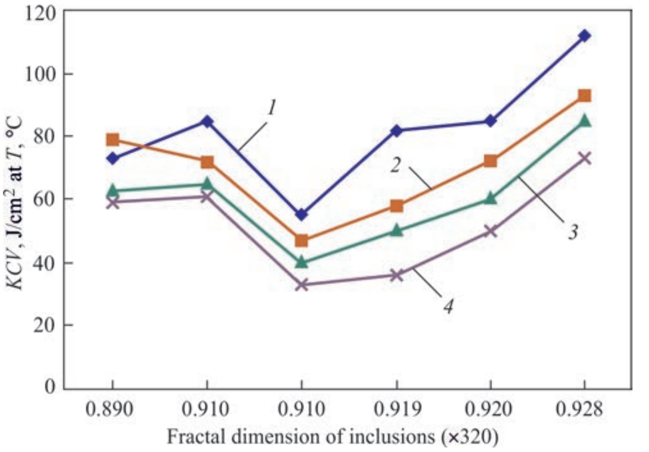

Figure 4. Interrelation of impact toughness and fractal dimension of inclusion size in the weld metal at the following temperature: *1* — 20; *2* — 0; *3* — –20; *4* — –40 °C

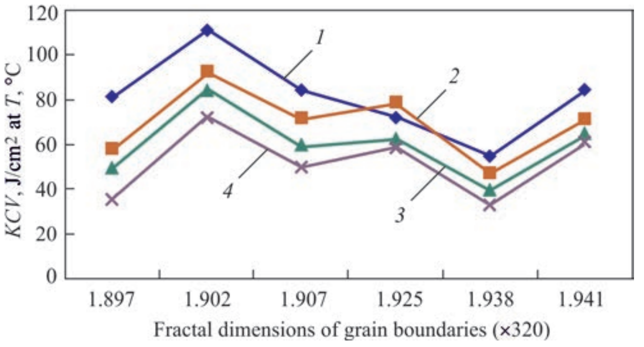

Figure 5. Interrelation of impact toughness and fractal dimensions of grain boundaries in weld metal microstructure at the following temperature: *1* — 20; *2* — 0; *3* — –20; *4* — –40 °C

Discussion of the results. Application of fractal analysis method enables numerical determination of such parameters of weld metal microstructure as the size of nonmetallic inclusions and branching of the grain boundaries that was impossible at analysis of metallographic images (Figure 3).

Level of impact toughness is an accumulating index, which is influenced not only by the volume fraction of nonmetallic inclusions in the metal, but also by their size distribution and level of homogeneity in the structure. At analysis of the factors, determining the mechanical properties of welds, it is necessary to take into account both the size of individual components of the structure, and their morphology. Obtained results show that the level of metal impact toughness increases with increase of fractal dimension of the nonmetallic inclusions (i.e. with reduction of the inclusion size) (Figure 4). Reduction of branching of intergranular boundaries influences the decrease of this index, despite the presence of rather fine inclusions in the structure (Figure 5).

Dependencies given in Figures 4–6, as well as the results of initial multifractal calculation (Figure 6), give a very general idea about the influence of both nonmetallic inclusions and grain boundaries on mechanical properties of weld metal. These results are indicative of the need to involve in the multifractal analysis the indices which describe the morphological features of the microstructural components, size distribution of nonmetallic inclusions, and level of solid solution alloying.

The outlined directions are the main objectives for development of computerization of metallographic investigations based on mutlifractal analysis.

Conclusions

The stochastic nature of fractal analysis of weld metal microstructure is shown. Examples are given of determination of the indices of fractality of the size of non-

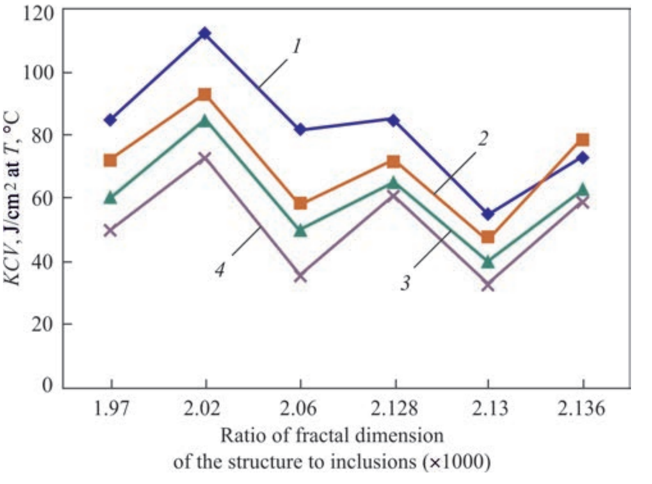

Figure 6. Interrelation of impact toughness and ratio of fractal dimension of grain boundaries and inclusion size in weld metal microstructure at the following temperature: *1* — 20; *2* — 0; *3* — –20; *4* — –40 °C

metallic inclusions and grain boundaries in the weld metal structure. The need to apply multifractal analysis to describe the influence of structural parameters on mechanical properties of welds was established. Investigation directions for development of multifractal analysis of welded joints were defined.

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