Fractal geometry in metallurgy of welding and coatings

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Application of new methods for the description of structure of metals and alloys, the identification of new quantitative structure-morphology tours are especially important to establish the relationship "structure - property" and predicting the properties of the welded metal on the basis of mathematical modeling. In our work we applied a fractal approach to the analysis of the following objects: structure of metal during welding, fatigue fracture surface of metal of welded joints, structure of coatings in micro-arc oxidation, macrostructure of the heat-resistant steels during electron beam welding.

Фрактурната геометрия в металургията на заваряване и покрития (Екатерина А. Кривоносова, Екатерина К. Кривоносова, Дмитрий Н. Трушников, Иля Пономарьов). *Прилагането на нови методи за описание на структурата на металите и сплавите, идентифицирането на нови количествени съотношения «структура-морфология» са особено важни, за да се установят отношенията "структура - свойства" и прогнозиране на свойствата на заварения метал на базата на математическо моделиране. В нашата работа ние прилагаме един подход на фрактурната геометрия към анализа на следните обекти: структурата на метала по време на заваряване, фрактурата на умора на повърхността на метала на заварените съединения, структурата на покритията при микро-дъгово окисление, макроструктурата на топлоустойчиви стомани по време на електронно-лъчево заваряване.*

Introduction

Fractal analysis in materials science is the mathematical algorithm of definition of the single numerical parameter for describing multilevel structures such as, in particular, structures of metals, fracture surfaces, porous structures of the coatings, fracture zones, structural boundaries of the ductile – brittle transition, etc.

Collaborative research metallurgists and physicists [1, 5] have shown that the structure of a wide range of materials is more informative to describe by the basis of the fractal approach. Fractal analysis in materials science is the mathematical algorithm to identify a single numerical parameter to describe the multi-level structures that in particular are the structure of metals, fracture surfaces, porous structure of the coating, the dynamical rows of parameters, the structural boundaries of the ductile-brittle transition etc.

In our work we applied a fractal approach to the analysis of following objects:

1. Structure of metal during welding;
2. Fatigue fracture surface of metal of welded joints;
3. Structure of coatings in micro-arc oxidation;
4. Macro-structure of the heat-resistant steels during electron beam welding.

Methods

The fractal approach is based on processing the fractal structure by scaling and on describing the distribution of any structural characteristic (or measure) in scaling.

The geometrical carrier in scaling is the mesh with square cells of different sizes.

In the fractal description of the structures of objects, the algorithm prepared using Mathcad and Matlab professional software, may be described as follows:

- the binarisation of the actual image of the structure, i.e. determination of the boundaries of recognition of half tones;
- the discrete approximation of the examined structures: the division of the appropriate binary images by the square grid, consisting of the identical cells, and allocation, through the cells, included in the ferrite region, of the values 0 and values of 1 to the single-phase light region of Widmannstatten ferrite. Thus, the initial

numbered image of the structure consists of a matrix containing 0 and 1;

- treatment of the resultant sets of the digital values (matrices) by division of the matrix to larger cells with the dimensions $L_i \times L_i$ (i=1,..., 32);
- construction, for each of division, of the characteristic measure in the form of the probability of distribution of units N_i, required for covering the ferrite field;
- the approximation of the dependence of $\ln P_i$ on $\ln L_i$ by the method of least squares and the determination of fractal dimensions D_f from the relationship:

$$P(L_i) = const \cdot L_i^{-Df}$$

Result

1. Fractal structure formation analysis and assessment of cold resistance of the weld metal of low-carbon steel for welding with coated electrodes

Engaging the concept of fractals allowed quantifying the degree of homogeneity (dispersion, fragmentation) of the structure of weld metal. Structural parameters relate to the level of the cold resistance welds.

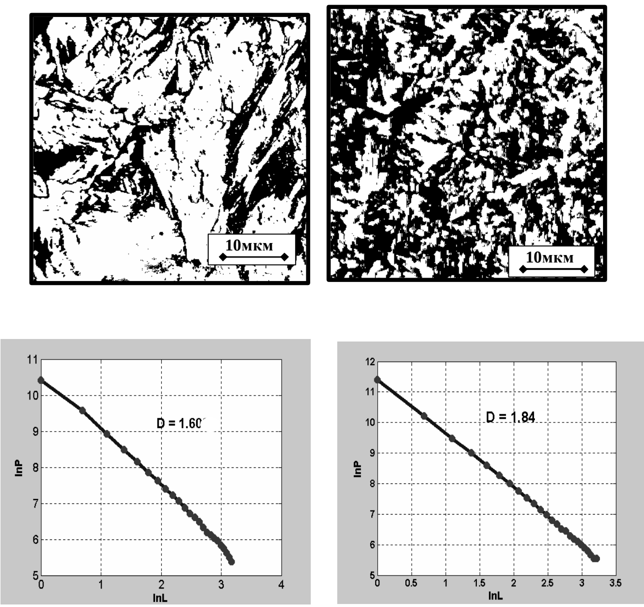

Fig. 1. Binary image center seam structures with varying degrees of homogeneity and determination of fractal dimension D_f

As an example, Fig. 1 shows the structure of the metal in the centre of the welded joint.

The microstructure was examined in a MIM-8 microscope, AverMedia digital video camera (resolution 630 . 420), and the translation of images on the computer screen was carried out using Amcar software. The welding of the specimens of St3 steel was carried out with E46 experimental electrodes, with the coating based on Ural ilmenite.

Comparison of the values of D_f with the topography of the structure shows that for a coarser structure with wide fragments of Widmannstatten ferrite extending through all fields of the grains of primary austenite, the value of D_f is lower and the structure is more homogeneous, approaching the conventional ferrite – perlite structure, with the higher values of D_f. On the whole, the value of D_f is in the range of 1.60–1.89. The statistical processing of the resultant values shows that there is a clear correlation between the values of D_f and T_{cr} (the critical brittleness temperature). Higher values of D_f are typical of the welded joints with higher cold brittleness resistance (T_{cr} is in the range of more negative temperatures: –50 .C). On the other hand, the weld metal whose structure is characterized by the lower values of Df is embrittled to a greater degree and the T_{cr} value of this weld metal is close to zero [2].

2. Fractal geometry of the fatigue fracture surface of weld joints and assessment of the fatigue crack growth rate

The results of investigations of special features of fatigue failure of the metal of welded joints using new methods of fractal analysis of the fracture surfaces in metals science of welding are presented. The aim of this study was the determination of the fractal dimension – the structural characteristics of the fatigue fracture surface – and of its relationship with the dynamic characteristics of fatigue failure, e.g. with the fatigue crack propagation rate.

The fractal dimension of the fracture surface is determined and its relationship with the kinetic characteristic of the process – the fatigue crack growth rate – is investigated.

Since the main property of the fractal structures is that they are invariant in relation to the scale, i.e. the relationships of the structure observed at a high magnification should also be valid at a lower magnification so that the fractal approach can be used efficiently in the analysis of macro-fractures, one of the special features of the application of the method of fractal analysis for investigating actual fatigue fractures of metals is the efficient identification of the investigated objects. If in the investigation of the structure in [3], the investigated object was the twodimensional image of the structure, in analysis of fractures it is necessary to deal with three-dimensional images.

In this study, the special feature of the actual image of the fatigue failure macro-fracture on the digital photograph is, firstly, the presence of a shadow on the relief (even if the light source is at the top) and, secondly, the correspondence of the colour tone of each fragment on the image to the height of the appropriate fragment on the actual fracture surface. Therefore, the images of the fracture surfaces, obtained by digital photography, were subjected to preliminary processing in the Adobe Photoshop software. The main stages of processing are the removal of the shadow on the image, formation of the effect of the section at a level of 0.2 mm in the thickness of the tone, and formation of the relief contour.

In this study, the measure used for the surface of fatigue fractures was the density of distribution of light areas on the conventional right-angled mesh, covering the section field. The distribution density can be calculated more efficiently by counting the number of cells P required to cover the fractal. Only the occupied cells are counted.

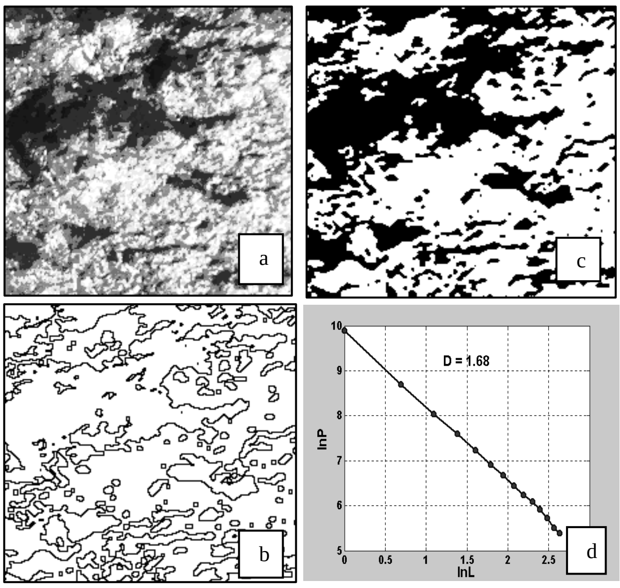

Fig. 2. Consecutive stages of processing the image of the initial fracture zone of the welded joint: (a) the actual image; (b), (c) the section of the fracture surface with the removed shadow and with the relief contour; (d) dependence of lnP on lnL, the fractal dimension of the fracture surface D = 1.68.

Analysis of the data shows that the fractal dimension of the microstructure of the individual fracture zones is associated with the fatigue crack propagation rate (Table 1).

Table 1

The fracture parameters and the fractal characteristics

N	Crack growth rate (m/cycle)	Fractal dimension D_f
Initial fracture zone		
1	$10^{-10} – 10^{-9}$	1.71
2	10^{-8}	1.68
3	10^{-8}	1.64
4	10^{-8}	1.68
Central fracture zone		
5	$10^{-8} – 10^{-7}$	1.65
6	10^{-7}	1.54
7	10^{-7}	1.58
8	10^{-7}	1.58

At a low fatigue crack propagation rate of 10^{-10} – 10^{-9} m/cycle, the fracture at the initial moment of loading is characterized by the fractal dimensional D < 1.70; when the rate is increased to 10^{-8} m/cycle, the fractal dimension decreases to 1.67 – 1.64; the central part of the fracture surface with the crack propagation rate of 10^{-7} m/cycle is characterized by the fractal dimension D = 1.60 – 1.55. Thus, the fractal dimension can be regarded as an adequate quantitative indicator of the fatigue crack propagation rate similar to the indicator such as the width of the grooves on the electron fractographs. At the same time, the labour content of fractal analysis of fatigue fracture is considerably smaller than that of conventional fractography.

3. Fractal geometry of the porous structure of coatings in micro-arc oxidation

It is shown that the service properties of coatings in micro-arc oxidation are strongly influenced by structural factors such as the uniformity of thickness and micro-hardness of the coating and also the presence of pores. The evolution of the porous structure in the thickness of the layer was studied by fractal analysis to determine the values of the fractal dimensions D – indicator of the homogeneity and fragmentation of the porous structure. The relationships between the technological parameters of the oxidation process and structural special features and, in the final analysis, properties of the coatings are determined [4].

Figure 3 shows the results of fractal analysis of the porous structure of the oxidized layer at different distances from the surface of the coating. The fragments on the left (a) show the actual image of the structure, the fragments on the right (b) show a binary image and (c) shows the dependence of the multi-fractal dimension N on the dimensional factor land the determination of the fractal dimension D.

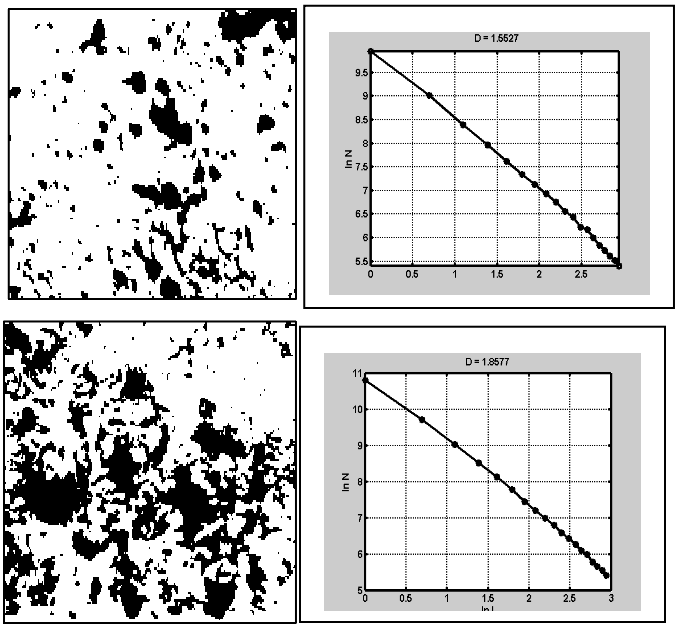

Fig. 3. Fractal analysis of the porous structure of the coating at different depths below the surface (the distance from the surface: top, 5 µm; bottom, 150 µm).

The fractal dimension of the internal porous structure for all the investigated specimens is greater than that of the external structure, indicating the higher homogeneity and ordering of the structure of the interlayer of the coating and the more uniform distribution of the pores in this coating.

4. Fractal analysis of the macrostructure of the heat-resistant steels during electron beam welding and assessment of the heat-resistance

The main problem of pattern formation in electron beam welding of low-alloy heat-resistant steels 15H1M1F type is the formation of unfavorable rough dendritic weld metal structures, which reinforces the tendency to liquation banding and micro-damaging. Features thermal welding conditions are complicated by a post-weld heat treatment on the structure and properties of welded joints. Temperature and time are features of welding that cause a significant change in the structure and natural decline of actual long-term strength of welded joints and other high-temperature properties.

Furthermore, the properties of the weld are unstable due to the unevenness of the cross section of the seam structure.

We studied the macrostructure of the weld metal and steel thermally affected zone 15H1M1F welded EBW without oscillations with oscillation along and across the interface.

To determine the heat-resistant properties of the used data [6] on the relationship limit long-term strength and hardness for steels of this type/

As a measure for fractal analysis of the structure of the material density of the sites we took ferrite - bainitic phases conventional rectangular grid covering the field of the section.

The range of long-term strength $\sigma_{100000}^{510^0 C}$ for the weld metal in the coordinate field "Hardness-fractal dimension" is shown in Figure 4.

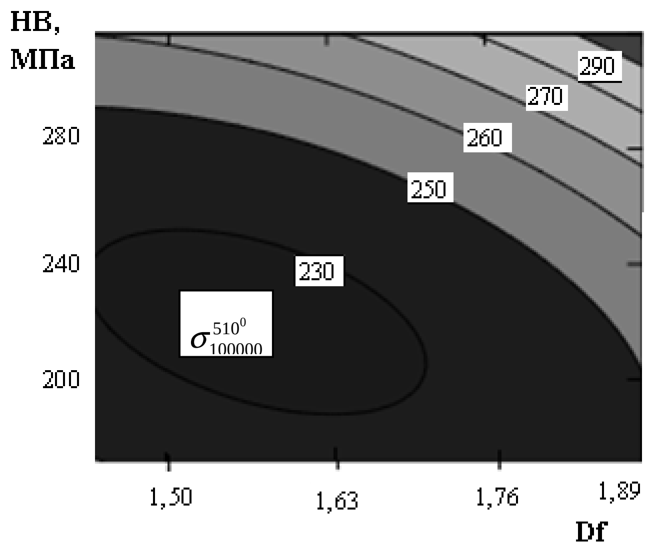

Fig. 4. Limit level lines long-term strength $\sigma_{100000}^{510^0 C}$ (MPa) for the weld metal 15H1M1F welded EBW in the coordinate field "Hardness-fractal dimension".

Conclusions

1. Examination of the special features of structure formation of the welded joints using the new method of fractal analysis for the materials science of welding has made it possible to obtain the values of the fractal dimensions which are indicators of the fragmentation of the structure, and use these values together with the criteria of cold brittleness resistance and cleanness of the welded joint, in the problems of modeling structure formation.

2. The experimental results obtained using the new method of fractal analysis in metal science of welding has been used to link the structural special features with the dynamics of fatigue failure.

3. The fractal analysis of the structure of the micro-arc oxidation coating showed high homogeneity and ordering of the structure of the internal layer of the coating and the more uniform distribution of the pores in this coating.

4. The fractal analysis of the macrostructure of the heat-resistant steels during electron beam welding showed that the highest heat resistance ($\sigma_{100000}^{510^0 C}$ = 270 - 300 MPa) have welds with fractal dimension of the structure D_f = 1.78 - 1.89.

REFERENCES

[1] E. Feder. Fractals. Moscow: Mir, 1991.

[2] E. A. Krivonosova. Fractal analysis of the formation of structure in welded joints. Welding International. Vol.19, issue 12, 2005, pp.976-970.

[3] E. A. Krivonosova & A. I. Gorchakov. Fractal analysis of the fatigue fracture surface of metal of welded joints. Welding International. Vol.27, issue 9, 2013, pp. 690-693.

[4] Ye. A. Krivonosova, A. I. Gorchakov & Yu. V. Scherbakov. Structure and properties of coatings in microarc oxidaion. Welding International. Vol.28, issue 10, 2014, pp. 816-819.

[5] R. M. Kronover. Fractals and chaos in dynamic systems. Fundamentals of theory. Moscow: Postmarket, 2000.

[6] I. Y. Klinov. Corrosion control in the chemical and petroleum industries. Sb.1, 1967, pp. 208.

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