Damage assessment of materials at low temperatures using the parameter of the fractal dimension of the microstructure

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Abstract. The article is devoted to the study of the evolution of the microstructure of steel 12Kh18N10T in the zone of intense deformation during fatigue loading. An algorithm for quantitative analysis of the microstructure of a material based on an indicator of fractal dimension is described. The studies have led to the conclusion that the fractal dimension of the microstructure of the material can serve as an indicator of its damage in a wide temperature range, and used as a quantitative criterion for the prefracture of the material, both during laboratory tests and during operation.

1. Introduction
Many structural elements work in conditions of low-cycle fatigue. During operation, cases of nucleation and development of a crack are often observed. At the stage before the onset and development of macrocracks, a period is identified associated with a change in the structure: the nucleation and accumulation of scattered microdamages, the nucleation and growth of micropores that do not interact with each other, and these processes pass secretly, with practically no visible external signs. [1, 2]. The second stage: the development of damage. There is a change in the physical and mechanical characteristics of materials, and for a number of materials and phase composition. The period of accumulation of damage ends with the formation of macrocracks and the destruction of the structure. Most often, the task is to assess the degree of degradation of the material and predict the residual resource during its operation. Therefore, the problem of controlling damage to the material, the ability to quickly assess the current state of the material of the structure without violating its performance in modern industry is quite relevant.

Non-destructive testing methods based on various physical phenomena, for example, changes in electromagnetic properties (eddy current, coercive force, Barkhausen noise, electric noise, etc.) are developed and improved to determine the damage to materials, to predict the time of the initiation of macrocracks [3, 4, 5].

Thus, the development of a metal analysis method with the identification of quantitative criteria for assessing its damage from the image of microstructures is of scientific interest. (Bodytext style).

2. Description of the method for assessing the fractal dimension of structures
One of the quantitative indicators of the metal structure is the indicator of the fractal dimension of the image (micrograph) of the D_{fr} structure. Fractal dimension is a coefficient that describes fractal structures or sets based on a quantitative assessment of their complexity.
Currently, there are a large number of programs that study the fractal dimension of structures in images. Many researchers define the fractal dimension of a structure as the fractal dimension of a grain boundary curve. In this case, a histogram of the brightness distribution is constructed and the grain separation boundary is determined by the position of the brightness maximum: that which is less than the brightness interval is considered to be material, that which is larger is the boundary. The correctness of the position of the boundaries is evaluated visually. As studies have shown in this calculation, the change in the position of the maximum of the module is only one unit, the fluctuations are (excluding boundary values) up to 0.1, which makes an error of up to 11%. The border estimate should not be on the difference between the maximum and minimum brightness of the picture, but on the sharpness of the transition from one grain to another.

For this, a two-dimensional wavelet function was used, which allows one to distinguish image differences. Depending on the scale factor, various values of the analyzed plane are obtained. A large number of wavelet functions allow us to identify various types of structural features. The most optimal for isolating the structure of the “Finish the First Level” wavelet. The wavelet transform method, in contrast to the brightness maximum cutoff method, allows grain boundaries to be detected, and the result is not very dependent on the image brightness and is able to work even with highly noisy microstructure images.

The fractal dimension, calculated along the boundaries of the grain structure determined using two-dimensional wavelet analysis, is much larger than that calculated by cutting off the brightness maximum, because Using two-dimensional wavelet analysis, the boundaries are determined more accurately, and a more complex bend line is obtained at the border.

Calculation of the fractal dimension of the material structure using wavelet analysis allows to increase the accuracy of calculating the fractal dimension, to eliminate the influence of the subjective factor on the result, to increase the calculation speed, and to automate the calculation process.

In figure 1 shows an algorithm for calculating the fractal dimension of an image using two-dimensional wavelet analysis and the result of the calculation in stages.

![Algorithm for processing and calculating the fractal dimension of the microstructure image.](image)

**Figure 1.** Algorithm for processing and calculating the fractal dimension of the microstructure image.

3. Equipment and research methods

For studies of the fractal dimension of the microstructure, fatigue tests were carried out. For testing, steel 12Kh18N10T was selected. This steel has been widely used for the manufacture of welded structures in cryogenic technology at low temperatures.
The chemical composition of steel 12Kh18N10T is as follows (%): C - 0.11; Si - 0.7; Mn 0.16; Ni - 10.2; S is 0.012; P is 0.008; Cr - 18.16; Ti - 0.6; Fe is the basis.

For fatigue tests, samples were made whose geometry is shown in fig. 2a. For testing, a specialized stand for fatigue testing was developed, the scheme of which is shown in fig. 2b.

![Figure 2. Sample geometry (a) and fatigue test bench (b).](image)

Test conditions: loading according to the cantilever bending scheme (cycle asymmetry coefficient R=-1) at a temperature t=+20°C and t= -100°C on a fatigue testing machine (fig. 2b) taking into account the requirements of GOST 25.502. The frequency of the elastoplastic cyclic loading was set using a frequency converter equal to 8.3Hz (500 cycles/min).

The stress amplitude (σ_max) was calculated based on the loading scheme, sample dimensions, and mechanical characteristics of the material. During the tests, the following were recorded: the number of cycles N and the amplitude of the stresses in the cycle σ_max. Studies were carried out at a voltage amplitude of 305MPa.

To conduct fatigue tests at low temperatures, a cryochamber was used to ensure uniform cooling of the sample and automatic maintenance of the test temperature due to the flow of cold air from a bath with liquid nitrogen. The temperature in the working zone of the sample was monitored using pt100 temperature sensors (fig. 2b).

Preliminary tests were carried out to estimate the number of cycles until sample failure (N_Σ). Further studies of the structures of materials were carried out before the start of testing and after operating time with a step of ~ 10% of the limit number of cycles N_Σ.

The microstructure was studied using a KYENCE-VHX 1000 optical microscope. The polished surface was etched in a 10% oxalic acid solution.

Damage (W) of the material was determined on the basis of acoustic measurements with subsequent signal processing [6].

To assess the fractal dimension of microstructures, software was developed in MATLAB based on the algorithm described earlier (see fig. 1).

4. Investigation of the relationship of damage with the parameter of the fractal dimension of the metal structure

The microstructures of the studied material at different stages of production and with different damage are shown in fig. 3 at test temperatures t = +20°C and t = -100°C.
Based on the analysis of microstructures with varying degrees of operating time and damage (W) and the estimation of fractal dimension (D_f) from the obtained images, the dependences of the fractal dimension of the microstructure of the working area of the sample (D_f) on the damage to the metal (W) at temperatures t = +20°C and t = -100°C (fig. 4).

Figure 3. Microstructures (x300) at different stages of operation and with different damage W.

Figure 4. Dependences of the fractal dimension of the microstructure (D_f) on damage (W) for steel 12Kh18N10T for test temperatures.

An analysis of the obtained dependences allows us to talk about the relationship between the fractal dimension of the microstructure in the working zone of the sample and the value of the metal damage. At low temperature t = -100°C, the nature of the dependence under consideration does not change, however, the values of the fractal dimension of the microstructure are slightly higher. As studies have shown, the values of the fractal dimension of the structure during the test also depend on the initial structure of the material.

The data obtained correlate with the results of a number of studies. So, in [7] it was shown that fractal dimension is an effective quantitative characteristic of the process of self-organization of the material structure during fatigue. It depends on the initial structure of the material, the state of its
surface layers and the number of loading cycles and can be used in the development of new criteria for the prefracture of materials. In [8-11], the relationship of fractal dimension with the mechanical properties of materials is shown, in particular, in works performed under the guidance of V.S. Ivanova [8, 9], it is proposed to use structural information as a measure of ordering of the system in case of symmetry breaking. On this basis, a technique for multifractal parameterization of materials was created.

5. Conclusion
1. The indicator of the fractal dimension of the microstructure of the material can serve as an indicator of its damage in a wide temperature range, and is used as a quantitative criterion for the prefracture of the material, both in the process of laboratory tests and in the process of operation.
2. To determine the fractal dimension of images of microstructures, their preliminary processing is necessary. For this, it is proposed to use an algorithm based on the wavelet transform of the image, which allows to increase the accuracy of determining the fractal dimension of the image and automate the processing process.

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