Evaluation of the mechanism of the destruction of metals based on approaches of artificial intelligence and fractal analysis

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Abstract. The article examines modern informational approaches to assess the degree of damageability of materials based on their fractograph images. The possibility of using the fractal dimension, wavelet transform and convolutional artificial neural networks for tiling and classifying the share of viscous and brittle destructions on fractures is shown. The results of experimental studies of the impact viscosity of materials with different types of crystal lattices in a wide range of temperatures are presented.

1. Introduction

One of the quantitative indicators of the structure and fractures of the metal is the index of the fractal dimension D. The fractal dimension is a coefficient describing the fractal structures or sets based on a quantitative assessment of their complexity.

Currently, there are a large number of programs investigating the fractal dimension of structures in images. In this case, the image is considered as an array of data.

In NSTU them. R.E. Alekseev developed a method for processing images of kinks (structure) of the material with the subsequent determination of its fractal dimension $D$. This technique is presented in the form of a diagram in Fig. 1.

To accurately determine the fractal dimension, it is necessary to identify differences in fracture images or material structures. The “Kenny's Detecting Overfalls” algorithm highlights the dramatic changes in an image by highlighting the module of its image gradient. The multiscale version of this differential detector is performed by smoothing the surface with an extended convolution kernel $Q(x)$. The two-dimensional wavelet function seems to be specially designed to highlight image differences: The maximum of the wavelet function is located in the center and gradually decreases at the edges. Depending on the scale factor, different values of the analyzed plane are obtained. A large number of wavelet functions allow you to identify various types of features.

The most optimal for the selection of the structure of the wavelet "Daubashi first level." The wavelet transform can focus on local signal structures. Features and nonsmooth structures often contain important information about signals. In the same way, for the analysis of images of microsections of material structures, the most important thing is the determination of the grain separation boundary, which is reflected by a sharp transition from a darker to a light image. Local
smoothness is characterized by a decrease in the amplitude of the wavelet transform with decreasing scale. Features and differences are distinguished by the study of local maxima in the wavelet transform at small scales.

Figure. 1. Method for determining the fractal dimension of the image

The advantage of the wavelet transform is its invariance to the noise of the signal. Even with a signal-to-noise ratio of one and a large number of outliers, the wavelet spectrum retains its structure.

The only drawback of a two-dimensional wavelet transform is the great computational burden. Nowadays, artificial neural networks (ANN) are increasingly used for image recognition and classification. In this connection, an attempt was made to recognize the image of fractures of the material using the INS.

Of particular interest is the use of wavelet analysis and ANN in the study and evaluation of the proportion of viscous and brittle fracture at the fractures, i.e. specimen failure surfaces, after the bend test. This will increase the level of use of fractography in the analysis of fractures and establish the nature of the destruction of the sample, and most importantly eliminate the human factor in assessing the proportion of viscous and fragile component in the fracture. At the same time, it is necessary to train ANNs on a large statistic of fracture surfaces.

2. Software implementation

To determine the fractal dimension (Fig. 1), the digital image was covered with nets with square cells. For each grid, the number of squares at which the boundary points are located was counted. The relationship between the number of squares and the size of the sides in double logarithmic coordinates is close to a linear relationship, where the angular coefficient k of the approximating straight line (obtained by linear regression) corresponds to the fractal dimension.

The calculation of the fractal dimension of the material structure using wavelet analysis allows to increase the accuracy of the calculation of the fractal dimension, eliminate the influence of the subjective factor on the result, increase the speed of calculation, and automate the calculation process. In the general case, the pattern of recognition and storage of data on fractures of the samples is shown in Figure 2.
To implement the algorithms proposed above, software (SW) was developed in the MatLAB environment, where preliminary image processing was carried out followed by the determination of the fractal dimension, as well as the development and training of a neural network to classify kinks.

The method of teaching a neural network - with the teacher, on pre-prepared data. Given the large amount of incoming data, there is a need for constant retraining of the neural network, in connection with which parallel computational approaches using graphics processors (GPU) and nVidia CUDA technology, in particular the specialized library cuDNN were applied.

It is worth noting that in order to achieve the minimum level of recognition error, it is necessary to divide the sample's fracture zone into sections (as a rule, not more than 100 sections). This procedure improves the quality of detecting the proportion of the viscous component in the fracture.

Thus, the developed software made it possible to obtain such quantitative indicators of fracture as:
1. The fractal dimension of the fracture $D$;
2. The proportion of viscous ($\% V$) and Fragile ($\% F$) components in the fracture.

### 3. Experimental studies
To test the proposed methodology for the quantitative analysis of metal fractures, impact bend tests were carried out.

For testing, materials with a different type of crystal structure were chosen: steel 20, 45, 12X18H10T, aluminum alloy D16 and titanium alloy VT8.

The tests were carried out in the temperature range from $t = -80$ °C to $t = + 20$ °C. To conduct tests at temperatures below room temperature, the sample was cooled in a special cooling chamber developed by us. The cooling process took at least 15 minutes at a temperature of 2-6 °C below the set point, then the samples were removed from the chamber, set on a pile driver and immediately tested (for no more than 4 seconds after the sample was removed from the bath), using the stop, for setting the sample [1].

The results of the fractographic studies of the fracture surfaces in shock bending of steel 45, titanium alloy VT8 and aluminum alloy D16 and steel 12X18H10T are shown in fig.3.
Figure 3. Fractograms: steel 45 (a), VT8 (b), D16 (c), steel 12X18H10T at $T = -40 \degree C$ (left) and $T = 20 \degree C$ (right) ($\times$ 2000)

During the tests, the impact strength of KCV was determined depending on the temperature. The analysis of fractures of specimens tested for impact bending determined the proportion of the viscous and brittle component in the fracture. The test results are shown in Figure 4.
4. Analysis of the results of experimental studies

As can be seen from Figure 4 for different materials, the level of toughness varies with different intensity.

- For D16, the level of toughness with a change in temperature in the range from 20 °C to -80 °C is practically unchanged and remains at a level of 20 J/cm². Only a viscous component is present in the kink over the entire temperature range under consideration.

- For steel 45, an intensive drop in toughness is observed already at a temperature $t < 20 \, ^\circ C$, the fraction of a viscous component monotonously decreases in fractures. The temperature of the viscous-brittle transition for steel 45 is $t = -28 \, ^\circ C$ (see Fig. 4b).

- For steel 20, the change in toughness is not monotonous, an intensive decrease in toughness begins at $t < -30 \, ^\circ C$. The temperature of the viscous-brittle transition for steel 20 is $t = -43 \, ^\circ C$ (see Fig. 4b).

- Titanium alloy VT8, compared with steel 45 and aluminum alloy D16, is almost 2 times higher than their impact toughness, which, as can be seen from the relationship (Fig. 4a), changes with less intensity. In the temperature range under consideration, a viscous component prevails in the fracture.

- Steel 12X18H10T, in comparison with other tested materials, has the greatest margin of toughness, which even at $t = -60 \, ^\circ C$ remains at 200 J/cm². In the temperature range under consideration, a viscous component prevails in the fracture.

From fractures of the samples, their fractal dimension was also determined. The results of determining the fractal dimension of the fracture of the studied samples are shown in Fig. 5a.

For steel 45, the change in fractal dimension occurs more intensely than for other materials. Analysis of Fig. 5 shows that with decreasing temperature, the structural stability of all materials decreases, since fractal dimension of fracture is growing.

According to the results of the correlation analysis, it was established that the fractal dimension of the fracture is closely related to the values of impact strength.

In this regard, it is necessary to note the relevance of the work performed at the Institute of Metallurgy and Materials Science. Baikov under the direction of V.S. Ivanova [2, 3], who proposed structural information as a measure of the orderliness of the system in the case of symmetry breaking. On this basis, a technique of multifractal parametrization of materials has been created. It is known that fractals have informational properties. In [2, 3, 4], the relationship between the fractal dimension and the mechanical properties of materials is shown. Also developed a new interdisciplinary scientific
According to the analysis of fig. 4 and 5, as well as from the results of the correlation analysis, it has been established that with a decrease in toughness, the fractal dimension of the fracture increases and, in addition, the intensity of changes in these characteristics also coincides.

![Figure 5. Fractal dimension of kinks $D$ versus test temperature $t$ (a), The dependence of the impact strength of KCV on the fractal dimension of the fracture of sample $D$ for steel 45 (b)](image)

Using the example of steel 45, for which, as studies have shown, as the temperature decreases, the fracture mechanism changes most intensively, we show the relationship between the fractal dimension of the kink $D$ and the impact toughness KCV. This relationship is shown in fig. 5(b).

As can be seen from Figure 6, the dependence of the impact strength KCV on the fractal dimension of the fracture of sample $D$ for steel 45 can be approximated by a second-degree polynomial with an approximation accuracy $R^2 = 0.99$. This relationship can be used to determine the impact strength of the fractal fracture dimension.

Also, as mentioned earlier, of particular interest is the use of wavelet analysis and ANN in the study and assessment of the proportion of viscous and brittle fracture at fractures, i.e. specimen failure surfaces, after the bend test.

To do this, we obtained fractographs of specimens tested for impact bending from steel 45 at various test temperatures and taking into account the data of the viscous and brittle component in fractures (Fig. 4). Using the data obtained, the ANT was recognized for the fraction of viscous fracture. The neural network was trained until the neural network recognition error reached 5%.

Table 1. Testing the quality of recognition of a viscous component using ANN

| Test temperature, $^\circ$C | -10 | -30 | -50 |
|-----------------------------|-----|-----|-----|
| The proportion of the viscous component in the fractures of the samples, % | Expert review 78 46 26 | ANN 81 49 24 |
| ANN recognition error | 4% 6% 8% |
Thus, it is shown that when recognizing a viscous component in fractures of steel 45 using the INS, the recognition error does not exceed 8%.

To simplify the analysis and systematization of the data obtained during the test, as well as after processing the sample fracture image, it is advisable to load the data into a special “Database of mechanical properties and parameters of the fracture material”.

5. Conclusions
1. A relationship has been established between the fractal values of fractures of specimens tested for impact from a value and the impact strength KCV. With an increase in toughness, a decrease in the fractal dimension of the sample fracture is observed.
2. The proposed intellectual system of analysis of fracture samples allows us to accelerate the process of recognition of isomal and selected essential features.
3. It is shown that when recognizing a viscous component in fractures of steel 45 using an INS, the recognition error does not exceed 8%.

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