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FRACTAL MODEL FOR ASSESSING THE MICROHARDNESS OF LOW-CARBON ALLOY STEEL AFTER CARBURIZATION

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The hardened surface of automatic transmission gear has been investigated by using fractal theory. Scanning electron microscopy (SEM) with microanalysis (EDX) were used to study the surface morphology and distribution of chemical elements of the hardened part. The carbon distribution on the surface as well as the influence of chromium on carbon diffusion during carburization have been investigated by using fractal theory. Structural changes via the cross section of the carburized layer were studied by measuring fractal dimensions. Comparison of the fractal dimensions and the level of microhardness over the cross section of hardened specimens allowed rapid assessment of the structural state increasing the tool service life. The results showed that both the mechanical properties and the surface fractal dimensions of the AISI 5120 steel differed greatly depending on the carbon concentration.

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INTRODUCTION

The transmission is a key element of any tractor and its durability depends on the quality of the components (including gears). If the gear is damaged during operations, it affects the entire transmission and may cause tractor failure and accidents.

In order to obtain high wear resistance of the finished part, combined with good fatigue properties, chemical heat treatment is usually performed. It is important to note that the structure and properties of the hardened part depend on the type of metal, the additives used, the conditions of the cementation process, and other factors. In production conditions, to fix structural changes, macro- and micro-scale levels of structure representation are usually used. At these scale levels, the structural changes that occur during carburization are not always quantified using traditional metallographic techniques. The reason for this may be the complex geometric configuration of the structure elements, which does not always allow obtaining satisfactory results of structure-property models. The complexity of identifying the metric (setting the distance between any pair of elements) is different for different areas of space and states of specific objects [1, 2]. When calculating the dimension of the object under study, the metric is often chosen arbitrarily, and this makes it possible to obtain more differentiated quantitative estimates. The dimension of many complex objects in nature is fractional and is described using fractal geometry.

Fractal structures are a class of complex geometric structures that are self-similar, and their geometry and dimension have a significant impact on their properties. Fractal analysis is very common in many areas of life [3], including mechanical engineering and biomedical engineering [4], in construction and architecture [1], in metallurgy when predicting quality criteria for finished products made of low-carbon steel; determining the corrosion wear of steel structural elements of nuclear power plants, to study the structures and properties of porous media [5, 6], etc.

In the case of metals and alloys, the fractal concept can be used to study the mechanisms of hardening of parts and establish the patterns of their destruction during operation. The theory of fractals has found practical application in [7-9], rough surfaces formed during wear and the assessment of their anisotropy, for the analysis of damaged surfaces of equipment as a result of erosion, and for the study of deformation-induced microstructures in metals [4]. The fractal dimension can be estimated using various methods, such as the variational method, the Minkowski method, the variation-correlation method, etc. It is important to determine the correlation between specific properties and the microstructure of the part surface, both after hardening and during operation.

Thus, the purpose of the research is to study the feasibility of using the theory of fractals to assess the effect of a carburized hardened surface of a tractor automatic transmission gear on its microhardness, taking into account the effect of alloying elements.

1. EXPERIMENTAL SETUP

2 pieces of gear teeth of an automatic transmission of a tractor made of structural alloy steel AISI 5120 were used for the experiments. The carburization depth, the homogeneity of carbon distribution and the level of microhardness of the hardened layer were assessed. The morphology of the original and hardened surfaces of the samples was studied using an optical microscope and a

JEOL JSM-6390LV scanning electron microscope (SEM) at an accelerating voltage of 20 kV. The chemical composition was studied by energy dispersive X-ray diffraction analysis (EDX). The microhardness was measured using a Vickers hardness tester. The load was 100 g. The assessment of microhardness and fractal dimension was carried out from the carburized surface (from the edge) to the center of the samples at 23 reference points for each of the two studied samples of steel AISI 5120 (Fig. 1). The first point was at a distance of 0.05 mm from the edge.

For theoretical studies, the images of the structure were converted into a 256-color format with shades of gray. The fractal dimension of the microstructure elements was determined using an automated program based on the convergence of the cellular and point methods. The calculation of the fractal dimension of the carburized surface is shown in Fig. 1. This example was made for the image of the microstructure of Sample No. 1 (tooth 1), shown in Fig. 3,a. The fractal dimension of the carburized surface was determined at the 7th iteration step based on the best convergence values of the cellular D_{fonk} = 1.885 and point D_{font} = 1.869 methods: $Df = (D_{fonk} + D_{font})/2 = 1.877$, and the dimension of carbides $Dt = (D_{tonk} + D_{tont})/2 = (1.995+1.995)/2 = 1.995$ was determined at the 5th iteration step (see Fig. 1).

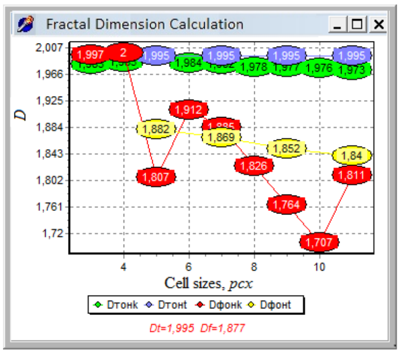

Fig. 1. Algorithm for calculating the fractal dimension of the structure (Fig. 3,a) of steel AISI 5120

2. RESULTS AND DISCUSSION

An important stage in the development of the parameters of the technology for hardening parts is the ability to evaluate the emerging structural changes and control the main mechanical properties that affect the service characteristics of machinery parts. Therefore, the main attention is paid to an integrated approach that combines experimental and theoretical studies, as well as the feasibility of using fractal formalism to model the structure and properties of low-carbon alloy steel AISI 5120 after carburizing. Conducted experimental studies revealed a gradient structure (Fig. 2) and micro-hardness in both samples. At given reference points, EDX studies were carried out on the distribution of chemical elements over the cross section of the hardened part (Table). The maximum carbon content at a distance of 100 µm from the surface in Sample 2 is due to secondary diffusion in the solid state. This results in a change in carbon concentration between the surface cemented layer (rich in carbon) and the inner core of the sample metal. As a result, there is an increase in the depth of carbon absorption with a decrease in its concentration on the surface. To register the structural changes in the carburized layer of mild steel at the microlevel, theoretical modeling was carried out depending on the distance to the surface of the samples. Based on the results of experimental structural studies, an analysis was made of the fractal dimension of the carburized surface of the samples depending on the proportion of carbon at the selected reference points.

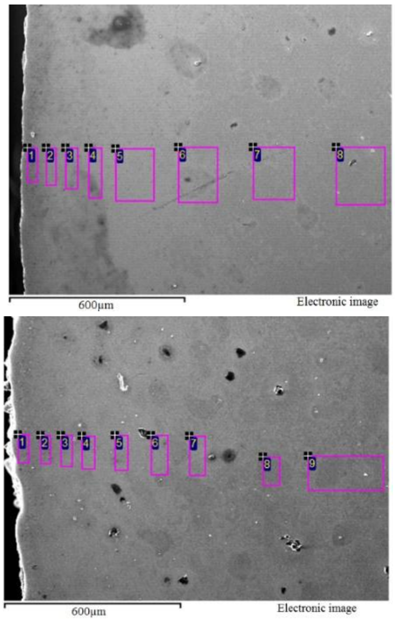

Fig. 2. SEM cross-sections of the carburized surface of samples No. 1 (a) and 2 (b)

EDX and fractal analysis

Spectrum	C	Si	Mn	Cr	Fe	D
Sample No. 1 wt.%						
1	28.83	0.24	-	0.85	70.08	1.984
2	18.23	0.20	-	1.05	80.51	1.968
3	25.34	0.25	-	1.01	73.39	1.972
4	22.16	0.21	-	1.05	76.58	1.971
5	16.89	0.10	-	1.11	81.90	1.849
6	21.10	0.15	-	0.92	77.83	1.961
7	16.16	0.26	0.12	1.03	82.44	1.837
8	15.42	0.38	-	0.99	83.21	1.813
Sample No. 2						
1	26.28	0.28	-	0.94	72.50	1.959
2	26.64	0.40	-	1.10	71.86	1.955
3	20.94	0.17	0.35	1.03	77.52	1.949
4	19.07	0.27	-	0.96	79.70	1.941
5	17.25	0.31	-	1.06	81.38	1.889
6	16.88	0.21	0.18	1.28	81.45	1.856
7	15.16	0.30	0.02	1.22	83.30	1.804
8	18.59	0.27	-	1.17	79.98	1.906
9	16.45	0.29	-	1.21	82.05	1.862

An increase in the carbon content causes an increase in the fractal dimension of the carburized surface. Changes in the fractal dimension for Sample 1 are fixed in the range of values: D_{max} = 1.984; D_{min} = 1.813. The dependence of the fractal dimension on the carbon content for Sample 1 has a polynomial character with a relatively high pair correlation coefficient of 0.8615 (see Fig. 3,a). The fractal function D(C) for Sample 2 also has an exponential character (Fig. 3,b). Such an increase in the fractal dimension is primarily due to the saturation of the surface with carbon up to 26.64%, which increases the compactness of its diffusion of the metal surface. Accordingly, the fractal dimension of carbon tends to the topological dimension of the surface $D \rightarrow 2$. A decrease in the carbon content to 15.16% leads to a decrease in the dimension of the carburized surface to 1.804.

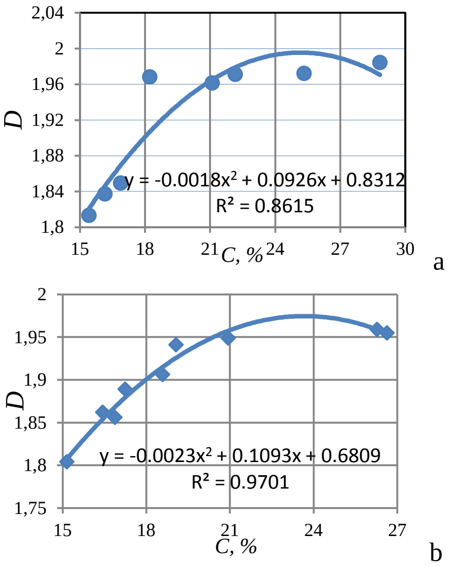

Fig. 3. Dependences of the fractal dimension of the carburized surface on the fraction of carbon for samples No. 1 (a) and 2 (b)

A change in the content of chemical elements on the surface of a material can also affect its morphology and fractal dimension. In [9], the influence of the content of chemical elements N, O, Zr on the fractal dimension of the ZrN coating surface was discussed. In this case, the surface morphology has a fractal nature due to the conditions of structure formation in an open system. Therefore, the effect of alloying elements on the example of chromium on the fractal dimension of the carburized surface was also investigated (Fig. 4). For Sample No. 2, a linear relationship is observed between the fractal dimension of the surface and the Cr content with a pair correlation coefficient of 0.64. This is explained by the fact that additional doping of austenite with substitutional elements (Cr in this case) increases the activation energy of carbon and, accordingly, reduces its diffusion mobility, i.e. enhances the braking effect. A decrease in the diffusion mobility of carbon leads, in turn, to a decrease in the compactness of its filling of the surface, and, as a consequence, to a decrease in the fractal dimension of the carburized layer. A one-to-one correspondence for Sample No. 1 between the Cr content and the dimension D was not revealed R^2=0.15. However, for both samples, a trend was recorded for the decrease in the fractal dimension of the carburized surface, depending on the increase in the chromium content. From these positions, by measuring the fractal dimension of the carburized steel surface, it is possible to register the effect of alloying elements on its morphology.

The effect of structural changes on the mechanical properties (microhardness) of gear teeth after carburizing has been also investigated. A decrease in microhardness indices from the surface deep into the samples and the formation of three zones after hardening were recorded: a carburized surface layer, up to 600 µm deep, transitional and base metal of the gear.

A higher gradient of the microhardness value was found across the section (from 50 to 3000 µm) in Sample No. 1. As a result of carburization, the hardness level increased by 35.7%: from 378.8 to 588.6 MPa units. For Sample No. 2, the microhardness indices changed over the cross section by 29.8%, which in units of hardness ranged from 305.8 to 524.0 MPa. The microhardness indices of Sample No. 1 up to a distance of 1650 mm, with the exception of the reference point of 1250 mm (383.1 MPa), are 100 MPa higher than those for Sample No. 2. The different level of microhardness for both samples is due to the inhomogeneous distribution of carbon.

The fractal dimension of the carburized surface of Sample No. 1 changes over the cross section by 8.4%: from 1.948 to 1.797. This indicator for Sample No. 2 changes over the cross section by 7.0%: from 1.953 to 1.826. The maximum values of the fractal dimension correspond to the highest microhardness values. Such an increase in the values of the fractal dimension of the carburized surface is explained by an increase in the proportion of carbon and the compactness of the filling of the structure as a result of carburizing.

Using the least squares method, the dependence of microhardness on the fractal dimension of the carburized surface was revealed (see Fig. 4).

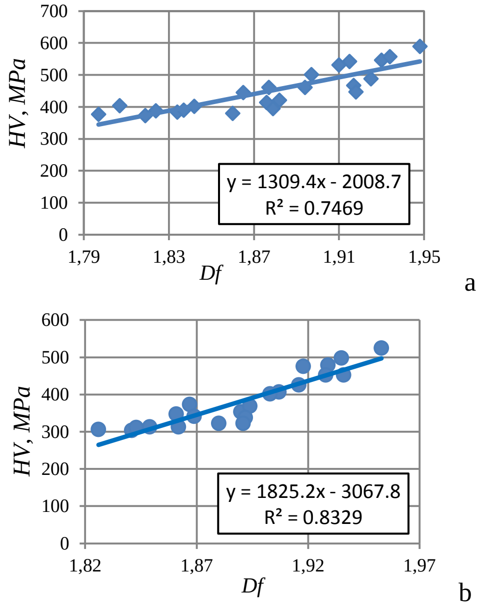

Fig. 4. Dependence of the fractal dimension on the microhardness of the carburized surface for Samples No. 1 (a) and 2 (b)

The estimated pair correlation coefficient was 0.75 and 0.83, respectively. These results indicate the existence of sensitivity of the microhardness of steel AISI 5120 to the fractal dimension of the structure of all transition zones of the carburized surface. It is possible that the revealed difference in the distribution of carbon and the level of microhardness is associated with the initial inhomogeneity of the steel (before hardening) and will greatly affect the uneven wear of the gear in operation. At the same time, the results of predicting the microhardness indicators of low-carbon alloy steel AISI 5120, based on the structure and carbon fraction after the carburizing process, allow us to use the fractal assessment as an indicator of qualitative transformations of the structure.

CONCLUSIONS

The results confirmed the expediency of using fractal formalism to model the structure and properties of a machinery part made of low-carbon steel AISI 5120 after carburizing, which made it possible:

– to register structural changes in the carburized layer of a tractor automatic transmission gear for its microhardness using the theory of fractals at the microlevel by measuring its fractal dimension depending on the distance to the surface of the samples. The results obtained indicate the sensitivity of the fractal dimension of the steel surface to the percentage of carbon in the range of values for Sample No. 1 15.42 wt.% C, 28.83 wt.% C, and No. 2 15.16 wt.% C, 26.64 wt.% C. When analyzing the images of the microstructure of the investigated steel AISI 5120 it was found that an increase in the carbon content in the above ranges causes an increase in the fractal dimension of the carburized layer to 8.4%;

– the fractal dimension as an indicator of changes in properties (microhardness), which allows to use assessment of microhardness depending on the carbon content in steel based on a fractal analysis of images of the structure. This is confirmed by fractal models for predicting microhardness indicators with a pair correlation coefficient $R^2 = 0.75…0.83$;

– based on the change in the fractal dimension of images of the carburized surface, the influence of alloying elements on the surface morphology was registered using the example of the influence of Cr. For both samples, a trend was recorded for the decrease in the fractal dimension of the carburized surface, depending on the increase in the chromium content.

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ФРАКТАЛЬНА МОДЕЛЬ ОЦІНКИ МІКРОТВЕРДОСТІ НИЗЬКОВУГЛЕЦЕВОЇ ЛЕГОВАНОЇ СТАЛІ ПІСЛЯ ЦЕМЕНТАЦІЇ

С.П. Романюк, K. Nowakowska-Langier, В.М. Волчук, А.В. Таран, Є.О. Нестеренко

За допомогою фрактальної теорії досліджено зміцнену поверхню шестерні автоматичної коробки передач. Для вивчення морфології поверхні та розподілу хімічних елементів зміцненої деталі використовували скануючу електронну мікроскопію (SEM) з мікроаналізом (EDX). Розподіл вуглецю на поверхні, а також вплив хрому на дифузію вуглецю під час цементації були досліджені за допомогою теорії фракталів. Структурні зміни через поперечний переріз навуглецьованого шару вивчали шляхом вимірювання фрактальних розмірів. Порівняння фрактальної розмірності та рівня мікротвердості по поперечному перерізу зміцнених зразків дозволило швидко оцінити структурний стан, збільшивши ресурс інструмента. Результати показали, що як механічні властивості, так і фрактальні розміри поверхні сталі AISI 5120 сильно відрізнялися залежно від концентрації вуглецю.