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NEW COMPREHENSIVE APPROACH TO MATHEMATICAL MODELING OF METALLOGRAPHIC IMAGES OF TOOL STRUCTURES

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To increase the operational durability of tools in production and operation, this paper proposes an integrated approach for processing metallographic images of tool structures at various stages of their life cycle. It is based on the use of the Thixomet Pro software and a specially developed optical-mathematical method, which supplements standard programs for searching for optimal properties and production parameters. The metallographic structural images, obtained by using both optical and electron microscopes, were evaluated with the analysis of pixels in photos. Changes in the structural components of the metal in the two zones (in the main part and at the edge of the working surface of a tool) were comparatively analyzed. During operation, the decomposition of less stable structural components occurs, and a decrease in the proportion of special carbides from 14.4% to 8.15% can be observed. This is caused by the influence of deformation localization, which leads to the fragmentation and alignment of dispersed carbides at an angle of 45° relative to the working surface of a tool deep into the tool under the action of stresses, which during operation are the centers of crack nucleation and development. At the same time, carbide decomposition as well as diffusion of carbon and chromium can be observed. Using the mathematical method for describing structural changes, it was found that under the influence of external factors at the edge of the working surface of a tool, the intensity of the resulting diffusion of chemical components is higher. In addition, zones of damage and maximum local heterogeneity associated with the presence of pores and cracks were identified. This technique made it possible to identify an increase in the anisotropy of properties, formed during operation and associated with metal degradation, and determine the degree of structural heterogeneity.

Keywords: *optical-mathematical method, image, structural heterogeneity, defects, carbide phase, diffusion.*

The ever increasing requirements for the reliability of modern equipment lead to the search for new methods and approaches in assessing its quality. The survivability of tools can be increased in various ways based on the assessment of metal behavior during operation, with the behavior depending on the stability of their structural components, presence of defects, as well as physical and mechanical properties. At present, to study structure, metallographic analysis is used, followed by the mathematical processing of the images obtained. Using the intensity-color characteristics of the images, nonmetallic inclusions are identified based on their color tone [1]. In the microstructure images containing contours, segmentation is used using the contour-structural method. Determined are the percentage of perlite and ferrite [2], and the size of non-metallic inclusions [3]. Digital image processing methods have been developed to ensure the non-destructive inspection of materials and identify various types of defects, such as cracks and scratches. There are programs for the analysis of flaw detection and metallographic images, which make it possible to automatically identify defects, make recognition of inclusions, and evaluate their percentage in the materials of products [4, 5]. Mathematical models of rough surface quality control and analysis of fatigue fractures have been formed [6]. However, the analysis of the existing and currently developed methods for assessing the structure of materials shows that they are not complex. They are intended only for structural analysis and do not consider the relationship between the chemical composition, structure, and properties of materials. To predict the behavior of the material in the manufacture of tools in production and their operation, structure formation modeling under various conditions of their use is very effective. In this study, a new approach is proposed that allows us to evaluate structure formation processes, select optimal solutions, and predict the behavior of technical systems. To do this, we used the optical-mathematical method for describing the processes of formation of the structure and properties of metal to increase the operational stability of tools.

The aim of the paper is to develop an integrated approach for processing metallographic images of product structures at various stages of their life cycle.

In this work, studies were carried out on the tools made of X12 steel after the end of their service life.

A comprehensive approach is proposed, which is based on the use of the standard Thixomet Pro software [7] and a specially developed optical-mathematical method for processing metallographic images [8] and estimating structural anisotropy.

Both the methods used are based on a combined assessment of metallographic structural images, obtained using both optical and electron microscopes, with the analysis of pixels in photos that have a color characteristic from 0 to 255 shades. In the previous studies, it was shown [9] that these colors were divided into 16 identical intervals, and described 3 groups of phases, which included 1 to 9 – ferrites (color shades from 0 to 153), 10 austenite (martensite) (color shades from 153 to 170), 11 to 16 – carbides (color shades from 170 to 255). A significant influence on the distribution of phases and their variability is exerted by the presence of carbon and alloying components dissolved in them, heat treatment, and deformation modes.

The analysis with the Thixomet Pro software of the structural images of the tool made of X12 steel, that were obtained after its use, revealed that during operation, the color characteristics of various phases change (Fig. 1), which indicates their degradation. The proportion of special carbides in the middle part of the tool, which was not exposed to deformation, is 14.4%, and they correspond to the color shades from 121 to 255 (Fig. 1, b).

After a comparative analysis of the changes in the structural components of the two zones of the tool (see Fig. 1), it became clear that during operation, at the edge of the working surface of the tool, the decomposition of less stable structural components occurs, and a decrease in the fraction of the carbide phase to 8.15% can be observed with a reduced range of color shades from 160 to 255 (see Fig. 1, d). The effect of deformation is also manifested in the fact that the fragmented carbides line up at an angle of 45° relative to the working surface of the tool deep in the tool during operation, and, taking into account the nature of the action of stresses, these zones are centers of crack initiation.

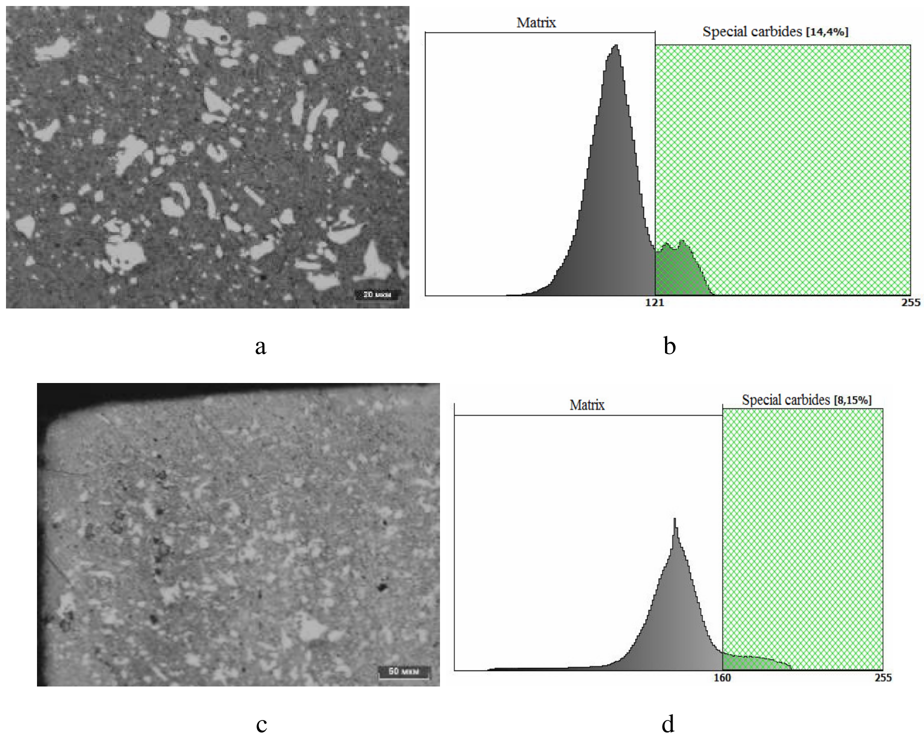

Fig. 1. Image of the structure:
a – in the middle section, c – at the edge of the working surface of the tool;
b, d – corresponding to the histograms of the structural components of the metal

At the same time, carbides decompose; and carbon and chromium diffuse, which is confirmed by the results of the local determination of these components by Electron probe microanalysis (Fig. 2). The chemical composition and special carbides of chromium in different areas of the product were determined locally. In the central part of the tool, they contain 44.11% of Cr (Table 1), whose concentration decreases significantly at the edge of the working surface of the tool, and reaches only 26.98 to 27.64% (Table 2).

Table 1. Chemical composition of the metal structure in the central portion of the tool (Fig. 2, a)

Spectrum	C	Si	Cr	Mn	Fe	Cu	Image zone analyzed
1	4.70	0.27	11.82	0.69	82.21	0.30	Matrix
2	8.55	–	44.11	–	47.34	–	Carbide

Table 2. Local analysis at the edge of the working surface of the tool in the carbide crushing zone during operation

Sprectrum	C	Na	Si	V	Cr	Mn	Fe	Mo	O	Note
1	4.53	–	–	0.15	27.64	–	29.53	0.34	37.81	Fig. 2, b
1	7.09	–	0.16	0.22	26.98	–	65.55	–	–	Fig. 2, c
2	3.67	0.28	0.33	–	8.28	0.39	87.06	–	–	

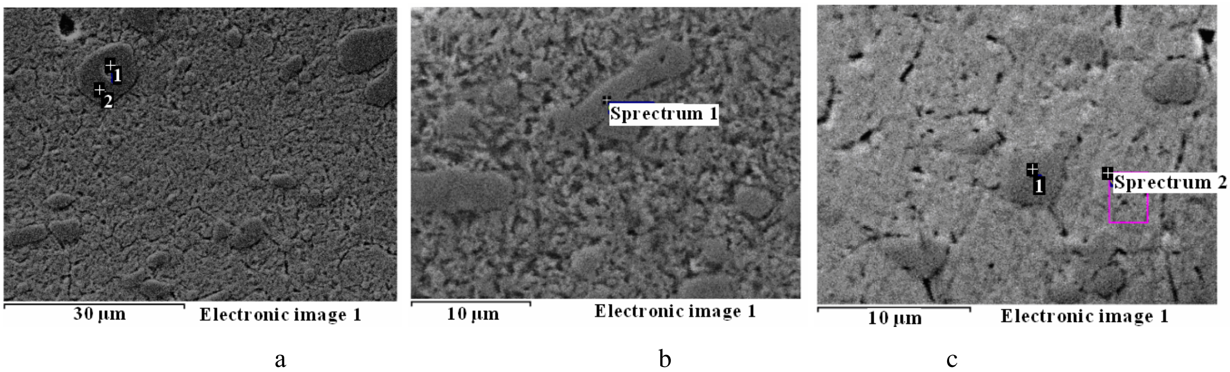

Fig. 2. Microstructure images:
a – in the central portion of the tool, b, c – at the edge of the working surface of the tool

It was found that, during operation, at the edge of the working surface of the tool, the carbon concentration in the carbide phase decreases too. The revealed local carbide heterogeneity (Fig. 3) is accompanied by a decrease in the chromium concentration at the edge of the working surface of the tool compared to the central portion of the tool by 6.7%, and an increase in the carbon content by 1.58 times (Table 3).

Table 3. Integral analysis of the central portion of the tool (Fig. 3, a) and at the edge of its working surface (Fig. 3, b)

Element	Weight analysis %	
	Central portion	At the edge of the working surface
C	6.85	10.83
Al	0.10	0.22
Si	0,28	0.22
Cr	12.17	11.36
Mn	0.44	0.41
Fe	78.65	64.55
Cu	1.07	1.21
Mo	0.45	–
O	–	10.75
Ni	–	0.17
S	–	0.14
Cl	–	0.07
V	–	0.06
Итоги	100.00	100.00

Comparison of the distribution of components during thermionic emission shows that the fraction of iron in small carbides decreases to a greater extent than the concentration of chromium decreases, and carbon is distributed more evenly over the zone being analyzed.

The image analysis showed that at the edge of the working surface of the tool, closer to the maximum stress zone (Fig. 3, b), the most intense diffusion of iron from chromium special carbide is noted.

The structure heterogeneity being formed (resulting from the fragmentation of doped carbides under the action of emerging stresses) on the tool cross section can significantly reduce the operational properties of the tool.

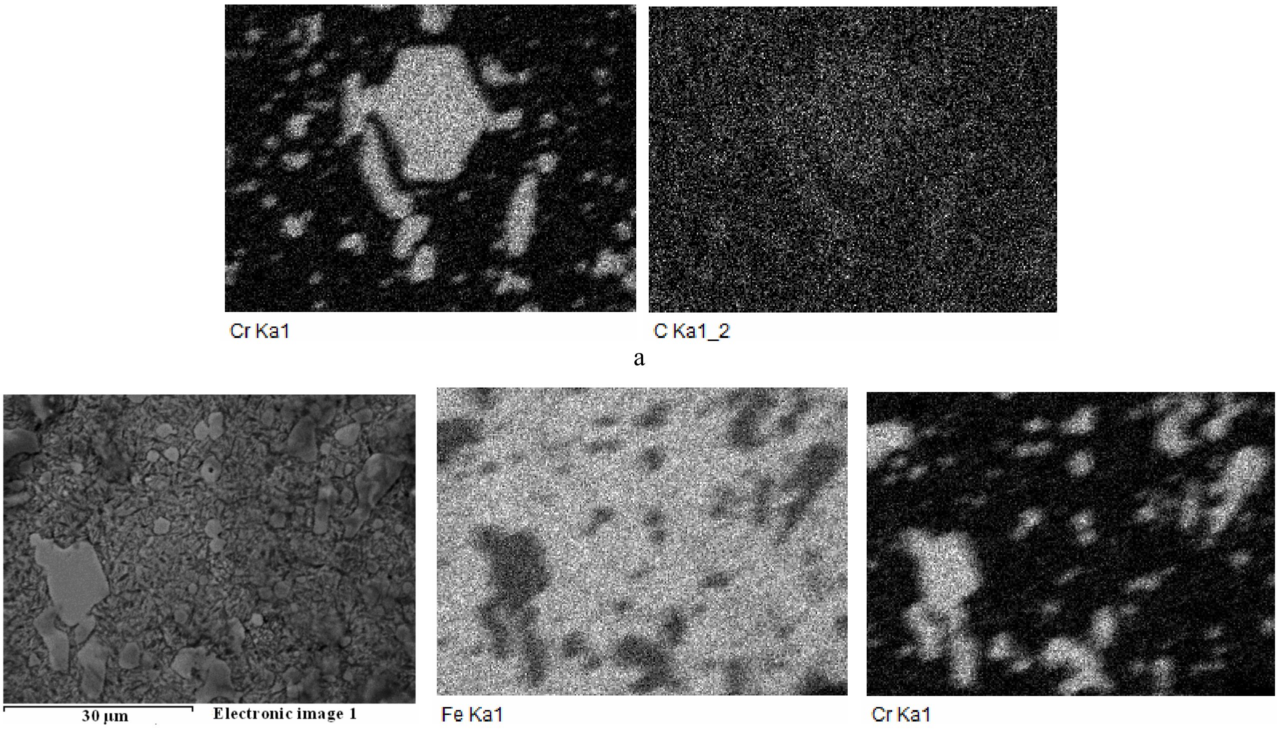

Fig. 3. Thermoelectronic emission:
a – distribution of components in the central portion of the tool,
b – distribution of components at the edge of the working surface of the tool

For the qualitative and quantitative analysis of the structure and estimation of dispersion within each phase related with the local heterogeneity identified, a method for the mathematical processing of metallographic images was proposed [9]. It is based on the analysis of pixels of the digital metallographic image obtained in horizontal and vertical directions with the definition of the following indicators:

– the absolute value of divergence (this indicator describes the density of an image fragment, the greater the divergence value, the more intensively the structural changes occur);

– the absolute values of the first, third and fourth Laplacians, respectively (describe the diffusion of chemical components);

– the generalized gradient was estimated in absolute value (it is the average effective color change rate, which corresponds to the intensity of the resulting deformations). These characteristics describe the energy parameters corresponding to energy dissipation.

For the metallographic analysis of the metal structure of the tool, a prepared cross section was used. A total of 17 photos of different areas of the tool were analyzed. Eleven images were obtained with an electron microscope and 7, with an optical one. The results of the values of the functions described above are presented in Table 4.

The first, fourth, fifth, sixth images from the electron microscope and the twelfth photo from the optical one relate to the edge of the working surface of the tool. Images 9–1 are the tool side surface that is subject to deformation during operation.

The results obtained make it possible to evaluate both the arising diffusion and the structural changes being formed because of deformation during the operation of the various zones of the tool. For this, the changes obtained in the function in different areas of the tool were compared. Since the principle of operation of microscopes and the locality of structure analysis are different, it is advisable to compare metallographic images separately for each of them.

Table 4. Values of the average functions obtained

Color	Mean-square color	Generalized geadient	Laplacian	Third Laplacian	Fourth Laplacian	Divergence	Photo No.
72.3	42.7	43.2	127.3	215.3	407.8	71.7	1
103.3	54.0	46.7	146.8	253.8	478.4	82.9	4
95.5	32.5	32.4	97.0	168.7	317.1	55.3	5
107.1	28.9	30.5	89.8	152.7	288.6	50.8	6
110.7	32.1	32.8	95.6	164.3	310.0	54.9	2
128.7	29.5	31.6	94.0	157.0	295.7	53,3	3
117.1	29.6	29.5	85.8	146.4	275.5	49.3	7
143.4	51.6	47.9	142.2	250.0	473.4	81,6	8
93.6	23.1	22.5	68.1	121.0	231.3	37.8	9
58.4	15.7	15.6	48.3	83.1	156.9	27.0	10
95.0	29.2	25.7	75.2	127.8	236.9	45.2	11
112.6	18.0	14.2	47.9	85.6	161.1	27.0	12
43.0	22.3	16.7	62.2	117.2	228.3	32.5	13
41.5	21.1	15.7	58.6	110.6	215.1	30.7	14
95.5	17.6	13.8	48.2	88.4	168.8	26.6	15
89.3	17.3	13.6	48.3	89.2	171.3	26.3	16
60.6	23.6	18.5	64.0	116.9	222.8	35.5	17
60.8	23.5	18.5	64.0	117.2	223.3	35.4	18

During the analysis of the images from the optical microscope, it was found that at the edge of the working surface of the tool, the energy parameters of dissipation are increased, characterized by the intensity of the arising diffusion processes and changes in fragment density.

In addition, the heterogeneity of the structure was evaluated both in the vertical and horizontal directions (Table 5). The closer this indicator to unity, the more uniform the structure being formed.

Table 5. Values of the average heterogeneity of the tool structure

Horizontal heterogeneity	Vertical heterogeneity	Photo No.
0.832	0.518	1
0.938	0.577	4
0.930	0.759	5
0.935	0.840	6
0.943	0.814	2
0.942	0.891	3
0.961	0.853	7
0.966	0.731	8
0.971	0.863	9
0.941	0.849	10
0.914	0.786	11
0.996	0.920	12
0.976	0.735	13
0.975	0.745	14
0.993	0.921	15
0.993	0.915	16
0.982	0.766	17
0.982	0.766	18

From the analysis of the data obtained, it follows that under the action of deformation at the edge of the working surface of the tool, a maximally homogeneous structure is formed both in the vertical and horizontal directions (see table 5, photo No. 12). In this case, zones with local damage and increased heterogeneity related with the presence of pores and cracks are metallographically detected, which affects both the strength and operational stability of the tool. The increased anisotropy of properties in this case determines the degree of metal degradation (typical for the vertical direction of heat removal from a cast billet). Such a direction of structural heterogeneity is always formed in the production of cast and rolled products. During operation, zones with lesser anisotropy of properties are damaged to a greater extent (carbides are crushed, diffusion processes are intensified), with their anisotropy approaching 1.0.

Conclusions

Comprehensive studies of metallographic images were carried out using the standard modern Thixomet Pro software and a specially developed and improved optical-mathematical method. This approach made it possible to detect changes in the phase composition and structural degradation by the variability of the carbide phase color characteristics related with the processes that occur during operation. Using the mathematical method for describing structural changes, the maximum local inhomogeneity at the edge of the working surface of the tool was simultaneously established, the inhomogenity being associated with the presence of pores and cracks.

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Новий комплексний підхід математичного моделювання металографічних зображень структури

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Для підвищення експлуатаційної стійкості деталей у виробництві та експлуатації запропоновано комплексний підхід обробки металографічних зображень структур виробів на різних етапах їх життєвого циклу. Він ґрунтується на застосуванні сучасної комп'ютерної програми Thixomet Pro та спеціально розробленого оптико-математичного методу, який доповнює стандартні програми з пошуку оптимальних властивостей і параметрів виробництва. Проведено оцінку металографічних зображень структури, отриманих на оптичному та електронному мікроскопах з аналізом пікселів фотографій. Порівняльно проаналізовані зміни в структурних складових металу двох зон (в основній частині і біля краю робочої поверхні виробу). В процесі експлуатації відбувається розпад менш стабільних структурних складових та можна спостерігати зменшення частки спецкарбідів від 14,4 до 8,15%. Це *викликано впливом локалізації деформації, що призводить до подрібнення і вибудовування дисперсних карбідів під кутом 45º по відношенню до робочої поверхні всередину деталі під дією напружень, які в процесі експлуатації є осередками зародження і розвитку тріщин. Одночасно відзначається розпад карбідів, дифузія вуглецю і хрому. За допомогою математичного методу опису структурних змін встановлено, що під дією зовнішніх чинників біля краю робочої поверхні вище інтенсивність дифузії хімічних компонентів, яка виникає. Крім того, виявлено зони пошкоджуваності та максимальної локальної неоднорідності, пов'язаної з наявністю пір та тріщин. Дана методика дозволила виявити підвищення анізотропії властивостей, що формується в процесі експлуатації та пов'язана з деградацією металу, визначити ступінь структурної неоднорідності.*

Ключові слова: *оптико-математичний метод, зображення, структурна неоднорідність, дефекти, карбідна фаза, дифузія.*

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