Розроблено методику та пристрій для визначення відносної зносостійкості матеріалів в умовах тертя по незакріпленому абразиву. Запропоновано методику, що дозволяє представити контури абразивних частинок у вигляді функцій та розрахувати параметр гостроти частинок SPL^m. Параметр SPL^m знаходиться у тісній кореляції з інтенсивністю зношування для абразивів різної форми

Ключові слова: абразивна зносостійкість, незакріплений абразив, параметри форми, перетворення Фур'є, ланцюговий код

Разработаны методика и устройство для определения относительной износостойкости материалов в условиях трения по незакреплённому абразиву. Предложена методика, позволяющая представить контуры абразивных частиц в виде функций и рассчитать параметр остроты частиц SPL^m, который находится в тесной корреляции с интенсивностью износа для абразивов различной формы

Ключевые слова: абразивная износостойкость, незакреплённый абразив, параметры формы, преобразование Фурье, цепной код

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DEVELOPMENT OF A METHOD AND AN APPARATUS FOR TRIBOTECHNICAL TESTS OF MATERIALS UNDER LOOSE ABRASIVE FRICTION

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1. Introduction

Wearing out due to friction against a loose abrasive is a common type of operational deterioration of equipment parts in such industries as oil and gas, mining, construction, and manufacturing as well as in the use of earthmoving, road-building, and agricultural machinery. A key factor that determines the wear resistance of mechanisms in such working conditions is a rational selection of materials for coating the work surfaces that are directly exposed to abrasive impact during operation. The existing approaches are insufficiently effective if they are based on empirical methods of selecting materials only by the parameter of their hardness, as in many cases there is a poor correlation between hardness and wear resistance due to the peculiarities of the microstructure of the surface layer, on the one hand, and specific contact-force action of abrasive particles with different morphological features, on the other. Therefore, there is a need to develop new methods and devices for tribological studies, which would allow producing an adequate assessment of the relative wear resistance of various kinds of materials and coatings, taking into account the geometric parameters of the abrasive particles.

The improvement of existing and the development of new methods of tribotechnical testing are the prerequisites for a rational selection of materials for strengthening mechanical parts under specific conditions and for creating new surfacing materials with predictable properties.

Given that under current conditions the range of surfacing materials is constantly expanding, and the requirements for their physical and mechanical properties remain high, the development of new methods and devices for the assessment of abrasive wear resistance is an important direction in modern tribology.

2. Literature review and problem statement

Currently, there are two main and most widely used methods for determining the wear resistance of materials under conditions of friction against a loose abrasive.

The standardized method according to GOST 23.208-79 “Ensuring of wear resistance of products. Wear resistance testing of materials by friction against loosely fixed abrasive particles” and its U.S. equivalent ASTM G65-16 “Standard Test Method for Measuring Abrasion Using the Dry Sand/Rubber Wheel Apparatus” entail wear of reference samples and test samples by abrasive particles that are supplied to the friction zone and pressed with a rotating rubber roller. This approach has the following disadvantages:

– failure to provide a high value of the force pressing the sample to the rubber roller;

– long-lasting tests (10 min for the reference sample and up to 60 min for the test sample);

– special requirements for surface samples;

– it is necessary to grind in the roller and to replace it regularly.

Among non-standardized methods, the most commonly used is the Lorentz force method [1] that simulates the maximum interaction of an abrasive particle placed in an environment of compressed abrasive masses with friction-tested surfaces. A significant limitation to the widespread use of this method is an insufficient exchange of the abrasive mass around the sample, which results in the wear area being enriched with crushed and blunt particles of reduced abrasive capacity: large grains split, and unsplit massive particles are shifted by centrifugal forces to the periphery of the test chamber.

Changes in the geometric parameters of the abrasive particles in the zone of interacting with the friction surface lead to changes in the wear rate, whereas saturation of the interaction zone of the sample surface with crushed particles of an abrasive environment changes the nature of the interaction: instead of wearing out, the working surface of the sample is loaded with the abrasive, which radically changes the mechanism of wearing out the tested surface.

The abrasive ability of the particles in terms of friction on a loose abrasive and on the basis of their shape is most commonly evaluated by a set of the shape parameters such as roundness (R) and aspect ratio (AR) [2]. The R parameter determines the degree of deviation from the ideal circular shape of a particle; it is calculated by the formula [3]:

$$R = \frac{L^2}{4\pi A_p}, \tag{1}$$

where L is the perimeter of a circle whose area is equal to the area of the particle projection; A_p is the area of the particle projection.

The parameter AR is defined as the ratio between the maximum Feret diameter (F_{max}) and the minimum Feret diameter (F_{min}), or as the ratio between the radii of the minimum internal and maximum external circles [4]. In some cases, the characteristics of the abrasive ability of particles across some extended surface are described through the parameter of the particle's convexity (C), which is a correlation between the area of a shape obtained by constricting an ideal membrane around a particle (Fig. 1, *a*) and the area of the particle's projection [5]:

$$C = \frac{(A_p + A_f)}{A_p}. \tag{2}$$

An increase in the C parameter leads to a linear increase in the wear intensity.

The results of the analysis that is given in [6] on the influence of particle's shape on the intensity of abrasive wear show that at using different abrasives the wear of a sample is greater if there is a larger SPL parameter, which is an angularity degree at the vertices of abrasive particles that go beyond the middle radius $\bar{r}$ (Fig. 1, *b*). Its value is calculated by the formula:

$$SPL = \sum_{i=1}^{N} \cos\left(\frac{\theta_i}{2}\right), \tag{3}$$

where N is the number of vertices, and θ_i is the value of the angles at the vertices.

According to [7], the size of the particles essentially affects the intensity of abrasive wear in studying abrasive wear resistance of steel friction in an Al_2O_3 environment. Moreover, its increase in the range of 50 to 180 mcm is found to increase wear by the following parabolic dependence:

$$k = 9.2\sqrt{d}, \tag{4}$$

where k is the coefficient of wear, and d is the average size of the particles.

A similar tendency was found in studying the wear of WC-Co alloys among SiC particles [8] whose size differed almost by an order of magnitude (17.5 and 180 mcm) and in studying abrasive wear of white cast iron reinforced with inclusions of carbide phases such as Me_3C among Al_2O_3 particles with sizes of 16 to 192 mcm [9].

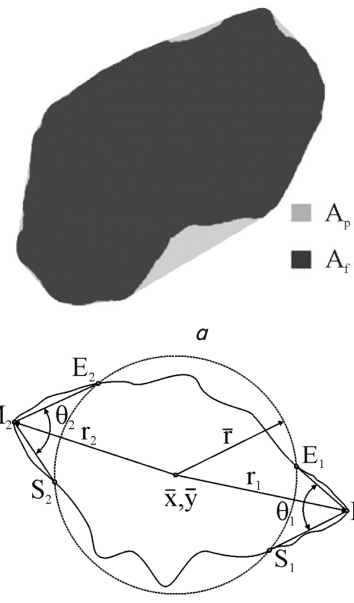


Fig. 1. Plans for calculating the shape parameters: *a* – convexity (C) [2]; *b* – a sharpness (spike) parameter (SPL) [3]

Thus, the abrasive ability of particles in tribological tests is determined by a complex analysis of criteria such as R, AR, C, SPL, and F_{max}, among which the most important criterion is SPL because its values are most closely related to the intensity of wear. For an objective assessment of the shape parameters of abrasive particles, it is essential to reproduce their contours as accurately as possible. Among the most effective ways of doing this is the reconstruction of the form by using a Fourier series; for example, according to [10], the shape of a particle may be reproduced by describing the shape in polar coordinates (r_i, θ_i) by the equation:

$$r_i(\theta_i) = r_0 + \sum_{n=1}^{N} \left[A_n \cos(n\theta) + B_n \sin(n\theta)\right], \tag{5}$$

where $A_n = \frac{1}{N}\sum_{i=1}^{N}\left[r_i \cos(i \cdot \theta_i)\right]$, $B_n = \frac{1}{N}\sum_{i=1}^{N}\left[r_i \sin(i \cdot \theta_i)\right]$ and $r_o = \frac{1}{N}\sum_{i=1}^{N}\left[r_i\right]$; N is the number of harmonic components.

This method of describing the contour allows distinguishing between a number of shape features (descriptors) that help classify the particles: circularity, aspect ratio, the number of vertices and their curvature. The value of the descriptor D_n for each n-th harmonic is determined by the equation:

$$D_n = \frac{\sqrt{A_n^2 + B_n^2}}{r_o}. \quad (6)$$

A more accurate method is to describe abrasive particles in the form of a closed circuit obtained by the Fourier transform of the particle's contours presented in the Freeman chain code (a boundary that connects the marginal points of a contour) in Fig. 2 [11].

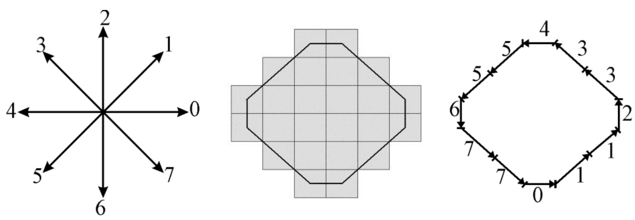


Fig. 2. A scheme of approximating the contour of a discrete image, using the Freeman chain code: *a* — direction vectors; *b* — an image of the object in pixels; *c* — the contour of the chain code

The Freeman chain code is approximated according to the Fourier transform procedure developed in [12]. The analytical dependence describing the outline of the image is represented as the following parametric equations:

$$x_p = x_c + \sum_{n=1}^{\infty} a_n \cos\left(\frac{2n\pi t_p}{T}\right) + b_n \sin\left(\frac{2n\pi t_p}{T}\right),$$

$$y_p = y_c + \sum_{n=1}^{\infty} c_n \cos\left(\frac{2n\pi t_p}{T}\right) + d_n \sin\left(\frac{2n\pi t_p}{T}\right), \quad (7)$$

where x_c and y_c are the coordinates of the center of mass of the particle; n is the number of the harmonics, t_p is the distance from the starting point to a given point p, T is the perimeter path of a particle. The Fourier coefficients (a_n, b_n, c_n, and d_n) are calculated by the formulae:

$$a_n = \frac{T}{2n^2\pi^2} \sum_{p=1}^{K} \frac{\Delta x_p}{\Delta t_p} \left(\cos\left(\frac{2n\pi t_p}{T}\right) - \cos\left(\frac{2n\pi t_{p-1}}{T}\right) \right),$$

$$b_n = \frac{T}{2n^2\pi^2} \sum_{p=1}^{K} \frac{\Delta x_p}{\Delta t_p} \left(\sin\left(\frac{2n\pi t_p}{T}\right) - \sin\left(\frac{2n\pi t_{p-1}}{T}\right) \right),$$

$$c_n = \frac{T}{2n^2\pi^2} \sum_{p=1}^{K} \frac{\Delta y_p}{\Delta t_p} \left(\cos\left(\frac{2n\pi t_p}{T}\right) - \cos\left(\frac{2n\pi t_{p-1}}{T}\right) \right),$$

$$d_n = \frac{T}{2n^2\pi^2} \sum_{p=1}^{K} \frac{\Delta y_p}{\Delta t_p} \left(\sin\left(\frac{2n\pi t_p}{T}\right) - \sin\left(\frac{2n\pi t_{p-1}}{T}\right) \right), \quad (8)$$

where Δx_p, Δy_p, and Δt_p are the displacement values of the i-th point relative to the (i+1)-th point along the axes x and y and the contour, respectively; K is the total number of points that form the circuit.

Thus, the effectiveness analysis of the methods of tribological research on the material's wear resistance under friction against a loose abrasive entails an obligatory consideration of changes in the morphological parameters R, AR, C and SPL under different test conditions. Therefore, a necessary prerequisite is to present the contours of abrasive particles in the form of analytical dependences of high accuracy.

3. The purpose and objectives of the study

The aim of this study was to develop a method and an apparatus for tribotechnical tests of materials under friction on a loose abrasive.

To achieve the stated goal, it was necessary to solve the following tasks:

– to develop a test unit for tribotechnical research based of the Lorentz force;

– to devise a method of evaluating the effectiveness of tribological studies of friction on the loose abrasive, taking into account the capacity of abrasive particles;

– to determine the correlation dependences between the shape parameters of abrasive particles that affect the abrasive wear resistance of the tested material.

4. Materials and methods of researching abrasive wear

Taking into account the shortcomings of the existing test methods, we developed a method and an apparatus for determining the relative wear resistance of materials and coatings [13], which allow testing materials for wear by a loose abrasive at a high specific pressure of the abrasive and at a significant exchange of the abrasive mass in the area of interaction between the working surface of the sample and the abrasive.

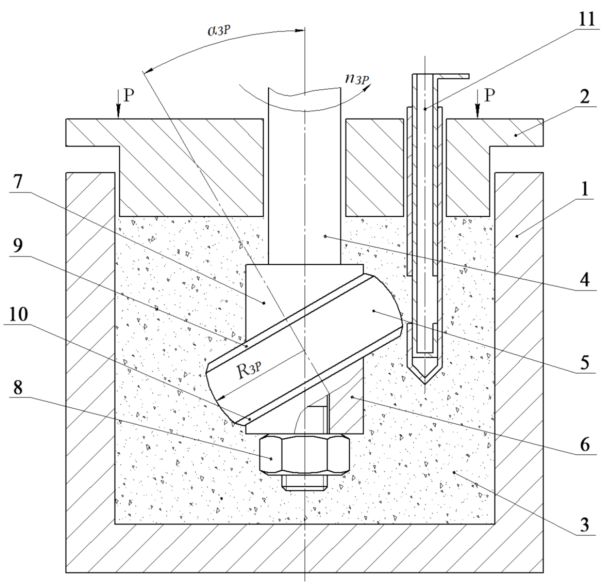
Fig. 3 shows a general view and a scheme of the developed apparatus for researching materials subjected to abrasive wear; the apparatus consists of a chamber 1, a cover 2, abrasive environment (grinding medium) 3, a holder 4, the sample 5, bushings 6 and 7, a nut 8, shims 9 and 10, and a shaft for the abrasive 11.

The device operates as follows. The holder 4, making a rotary motion with frequency n_s, ensures rotation of the sample 5 of the test material and thus creates a tribointeraction between the abrasive environment 3 and the working surface of the sample 5, causing deterioration of the latter. The sample 5 is installed on the holder 4 at an angle α_s to the holder axis. This is achieved with two cylindrical bushings 6 and 7 one end of which is set askew to the axis at an angle equal to the angle of the sample α_s; it is fixed with the nut 8. The bushings 6 and 7 are placed on the holder 4, with their sloping surfaces towards the end surfaces of the sample 5. The sample 5 gets fixed on the holder 4 by tightening the nut 8. The spherical radius R_z (15 mm) of the lateral surface of the sample 5 provides a constant speed of interaction between the surface being worn and the abrasive 3.

By applying force P to the cover 2 R, the abrasive environment 3 is compressed in the chamber 1, thereby creating pressure of the grinding medium 3 on the working surface of the tested sample 5.

Placing the sample 5 at the angle α_s to the axis of the holder 4 in its rotation causes intense mixing of the abrasive medium 3 and thus involves renewal of the abrasive in the work area, which ensures the maintenance of stable testing conditions.

a



b

Fig. 3. An apparatus to study material's abrasive wear resistance: *a* — a general view; *b* — a scheme (the references are in the text)

The slope angle of the sample 5 to the axis of the holder 4 is chosen in the range of 10° to 30°, which is explained as follows. At an angle less than 10°, the mixing of the abrasive and thus it renewal will be small, which will ultimately lead to a deterioration of the test conditions and a loss of accuracy and reliability of the research results. When the sample angle is bigger than 30°, the deterioration will largely happen to the end face of the sample 5 rather than to its lateral surface. Since the interaction conditions for the frontal surface of the sample are changeable (a variable speed of interaction and a different pressure of the abrasive environment 3), the obtained test data will be of low accuracy.

Placing two shims (9 and 10) in contact with the end surface of the sample 5 provides in-test wear of only the lateral surface, where the test conditions are constant and controlled. The result is increased reliability and accuracy of the tests.

The value of depreciation is determined by weighing the sample on analytical scales before and after the test.

The advantages of this method lie in the simplicity of its implementation as well as in high accuracy and information content of the obtained test results.

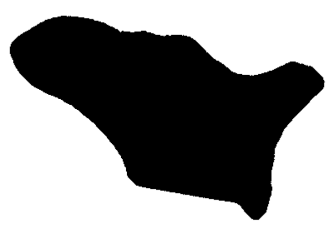
The designed apparatus, subject to the conditions of equipment parts operating in the oil and gas industry, is set the basic parameters of the tests: the test time t=900 seconds; the rotation frequency n_s=1.7 sec^{-1}; the unit load P=5 MPa; the abrasive – black silicon carbide 54C F20 TU U 24.1-00222226-059:2006.

For a comparative analysis of the abrasive, samples of 50 particles were selected in the initial state and after the test by the Lorentz force method and the developed technique [13].

The pictures of the abrasive particles were obtained using the stereoscopic microscope MSB-2, equipped with the digital camera glass eTREK UCMOS 5100. In order to obtain binary image projections of the abrasive particles, the shots were processed through the software Image Pro Plus 6.1 and ImageJ 1.50g. The binary images of each particle were used to calculate the parameters R, AR, C, and F_{max}. The SPL parameter was calculated by the improved method, which was applied as follows:

(1) using the module ChainCoder of the SHAPE program [14], the images of the particles (Fig. 4, *a*) were defined by the Freeman chain code (Fig. 4, *b*), which reconstructed the contour (Fig. 4, *c*);

(2) using the module CNC2NEF of the SHAPE program to find the center of mass of the particle, its largest radius located on the horizontal axis (Fig. 4, *d*), and Fourier coefficients (a_n, b_n, c_n, and d_n) for the 50 harmonics;



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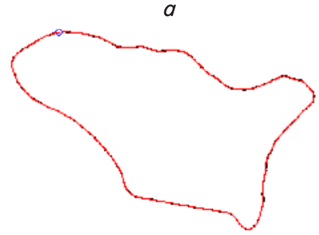

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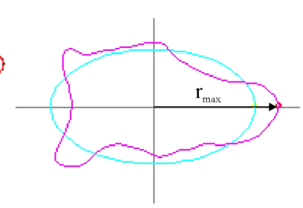

d

Fig. 4. The stages of reconstructing the particle contour: *a* — the original image; *b* — a chain code; *c* — reconstruction by the chain code; *d* — reconstruction by Fourier coefficients

(3) Fourier coefficients were used in parametric equations (7); it was assumed that $\frac{2n\pi t_p}{T}=\theta_i$, where θ_i was the corner of the radius vector varying from 0 to 2π with increments of 0.01 radians; x_c and y_c were assumed to be equal to 0. Thus, the parametric equations (7) to describe the contour were the following:

$$x(\theta_i)=\sum_{n=1}^{50} a_n \cos(n\theta_i)+b_n \sin(n\theta_i),$$

$$y(\theta_i)=\sum_{n=1}^{50} c_n \cos(n\theta_i)+d_n \sin(n\theta_i), \quad (9)$$

which made it possible to present the outline of a particle in polar coordinates of the radius vector as $R(\theta_i)=\sqrt{x(\theta_i)^2+y(\theta_i)^2}$ (Fig. 5). In areas beyond the average radius r_m, we measured the sharp peaks, or spikes (sp1, sp2, and sp3);

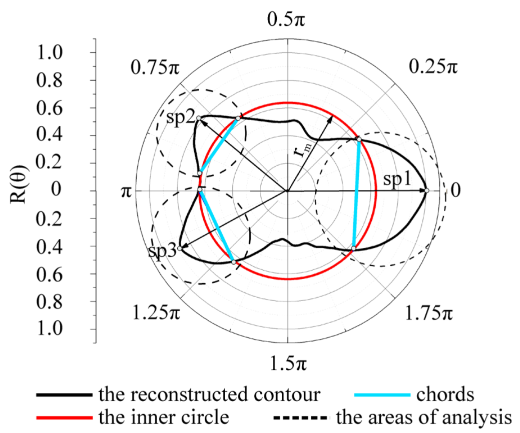

Fig. 5. A scheme of determining the sharp peaks of the particle contour

(4) for each detected sharp peak, we found the chord length (CL) received at the intersection of the circle with the radius r_m and the particle contour, which was followed by developing the profiles of the peaks of the abrasive particles in coordinates: (CL; $\Delta R=R(\theta_i)-r_m$) and approximating them with a piecewise linear function (Fig. 6) of the following type:

$$y=a_1+k_1x \text{ at } (x<x_i),$$

$$y=a_1+k_1x_i+k_2(x-x_i) \text{ at } (x\geq x_i); \quad (10)$$

(5) the values of the angle coefficients of the straight lines k_n and k_{n+1} were used to determine the angles θ_i and the sharpness parameter by formula (3).

The procedure was used to determine the sharpness parameter SPL for 150 particles. To assess the impact of the SPL parameter on the abrasive capacity, its value was calculated for particles whose abrasive ability was known from literary sources [6, 15]. A comprehensive assessment of the abrasive capacity was carried out by a parameter that was a product of all factors that increase the abrasive ability of particles [8]. For this case, the value was defined as: K_{abr}=SPL·R·AR·C. The impact of the dimensions was assessed by equation (4).

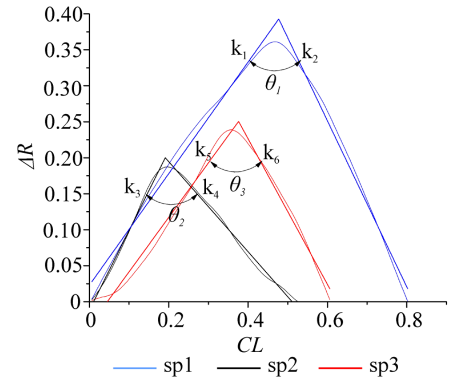

Fig. 6. An approximation of sharp peaks of a particle contour by a piecewise linear function

5. The results of the microscopic studying of abrasive particles

The calculation results for the parameter SPL^m for 5 abrasive particles of similar size and different shapes (Fig. 7) show that the calculation using the suggested method can produce more accurate results than the method suggested in [6]. In this case, the values of SPL^m are closer to the values of the SPQ parameter [15] and are within the error (Table 1). This is because during the approximation of sharp peaks that go beyond the radius r_m (Fig. 5) their contours are approximated with straight lines using the Levenberg-Marquardt algorithm (LMA). As a result, the obtained straight lines do not cross the intersection points of the inner circuit with the particle contour, which makes it possible to avoid getting inflated results of the SPL parameter and to approximate the calculated values to the SPQ parameter.

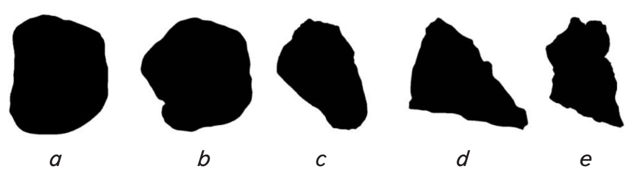

Fig. 7. The abrasive particles of known abrasive resolutions [6, 15]: *a* – silicon; *b* – granite; *c* – SiC; *d* – quartz; *e* – Al_2O_3

Table 1

Shape parameters of an abrasive with a known abrasive ability

Abrasive	I_h, mm/min	SPQ [15]	SPL [6]	SPL^m	AR	R	C	K_{abr}
Silicon	2.05	0.19±0.08	0.63	0.22	1.22	1.18	1.020	0.266
Granite	2.23	0.25±0.11	0.86	0.18	1.05	1.21	1.028	0.225
SiC	2.94	0.42±0.14	0.71	0.37	1.66	1.47	1.037	0.566
Quartz	3.43	0.53±0.14	0.86	0.56	1.62	1.67	1.074	1.010
Al_2O_3	3.89	0.6±0.14	0.71	0.58	1.65	1.84	1.107	1.183

The results of the comparative correlation analysis (Fig. 8, *a*) show that the SPL^m parameter is in close correlation with the wear intensity (the adjusted coefficient of determination R^2=0.92), and the accuracy greatly exceeds the SPL measured by the method of [6]. This makes it almost identical to the SPQ parameter (R^2=0.98) and suitable for assessing the wear rate depending on the shape of the abrasive particles, of both traditional abrasives from oxygen and oxygen-free ceramics and superhard materials of various dispersion, of a distinct homogeneous microstructure structure, and with the presence of a significant number of sharp cutting peaks of the crystal structure [16]. With the use of the complex parameter K_{abr}, the correspondence between the calculated (PV) and measured (OV) values of wear increases (R^2=0.95), and it is described by the regression equation:

$$I_h = 1.755 + 1.772K_{abr}. \quad (11)$$

Thus, equation (11) makes it possible to determine the relative ability of abrasive particles by the measured parameters of the contour shape.

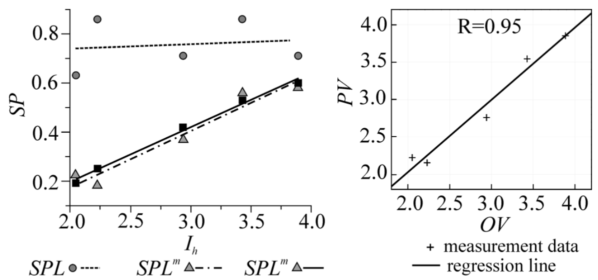

Fig. 8. The results of the correlation analysis: *a* — the correlation between the parameters of sharpness and wear intensity; *b* — the results of the regression analysis between the wear intensity and the comprehensive parameter K_{abr}

Fig. 9. The morphology of the abrasive particles of SiC: *a* — before the tests (F1); *b* — after testing by the method of the Lorentz force (F2); *c* — after testing by the improved method (F3) (with the test duration of 900 seconds)

The results of the microscopic studies of abrasive particles show that particles of SiC in the initial state (F1) have a clear faceted shape (Fig. 9, *a*), which is caused by the conditions of their production, namely by carbothermal restoration with subsequent milling, during which, as a result of dynamic performance of ground bodies, there appears an intensely brittle fracture of particles along crystallographic planes due to high rigidity of covalent bonds in the crystal lattice of SiC. After the tribotests, there is a natural reduction in the size of the particles and a change in their shapes due to abrasion on the metal surface. Moreover, testing by the method of the Lorentz force (F2) reveals these changes more clearly in comparison with the advanced technique (F3) (Fig 9, *a, b*). According to the statistics (Fig. 10, *b–e*), the highest values of all the measured parameters are those of SiC particles in the initial state, and the lowest values are obtained in the tests by the technique of the Lorentz force. The shape of the particles after testing by the optimized method acquires intermediate values of all the parameters.

The quantitative comparative analysis of distributing size frequencies (Fig. 10, *a*) and shape parameters (p) (Fig. 10, *b–e*) shows that the distribution of shape frequencies (N) is highly accurately (R^2>0.8) described by the log-normal law of distribution of the following type:

$$N(p) = \frac{A}{\sqrt{2\pi}wp} e^{-\frac{\left[\ln\frac{p}{p_m}\right]}{2w^2}}, \quad (12)$$

where A and w are factors, and p_m is a mean (median) value of the parameter.

Moreover, the calculated values of the mode and the median of the distributions of all the parameters for fractions F1 and F3 are closer than for fractions F1 and F2 (Table 2). This indicates that the use of advanced techniques reduces the change in the size and shape of particles compared to the initial state and, therefore, provides higher capacity of abrasive particles.

Table 2

The difference between the medians (ΔMed) and the modes (ΔMod) of distributing the frequency of shape parameters in the initial abrasive and after testing

Fraction	F_{max}		R		AR		C		SPL^m	
	ΔMed	ΔMod	ΔMed	ΔMod	ΔMed	ΔMod	ΔMed	ΔMod	ΔMed	ΔMod
F2	0.165	0.182	0.129	0.111	0.061	0.046	0.019	0.019	0.046	0.061
F3	0.772	0.783	0.202	0.187	0.163	0.183	0.037	0.037	0.085	0.124

6. The discussion of the research results

The analysis of particles by extreme values of shape parameters shows that within each tested fraction there are particles that are characterized by the maximum or minimum values in several parameters at once (Fig. 10, *f*). It concerns, in particular, particle № 24 of fraction F1 in the parameters R and C, particles № 33 and № 7 of fraction F2 in the parameters R, C and SPL^m, and particles № 2 and

№ 46 of fraction F3 in the parameters R, AR, C and R and SPL^m, respectively.

Therefore, we can conclude about the existence of a correlation between the parameters of the form. It was determined by a regression analysis in which the dependent factor was the SPL^m parameter, and the role of independent variables was performed by the parameters R and C. The obtained regressive dependences are sufficiently precise in describing the expected values of the SPL^m parameter both within each fraction (Fig. 11, *a–c*) and for all studied particles (Fig. 11, *d*).

As a result of the regression analysis, we have obtained an equation that determines a correlation between the sharpness parameter SPL^m and the parameters R and C:

$$SPL^m \approx 16.8 + 4.64R - 1.42R^2 - 35.93C + 16.11C^2. \quad (13)$$

The comparative evaluation of the efficiency of the improved and standard methods for fractions F3 and F2 was conducted by the ratio of wear intensity I_h3/I_h2, which was determined by calculating the coefficients $K_{abr}3$ and $K_{abr}2$ according to the average shape parameters within the relevant fractions and their use in equation (11). Given that the effect of the size of the abrasive particles on the wear rate ratio is described by equation (4), the overall ratio for the assessment of the relative wear rate becomes as follows:

$$\frac{I_h3}{I_h2} = \frac{1.755 + 1.772 \cdot \overline{SPL3} \cdot \overline{R3} \cdot \overline{AR3} \cdot \overline{C3} \cdot 9.2\sqrt{\overline{F_{max}3}}}{1.755 + 1.772 \cdot \overline{SPL2} \cdot \overline{R2} \cdot \overline{AR2} \cdot \overline{C2} \cdot 9.2\sqrt{\overline{F_{max}2}}}, \quad (14)$$

which, after applying the average statistics of its value, is:

$$\frac{I_h3}{I_h2} = \frac{1.755 + 1.772 \cdot 0.4633 \cdot 1.3358 \cdot 1.5974 \cdot 1.0735 \cdot \sqrt{1.7}}{1.755 + 1.772 \cdot 0.3993 \cdot 1.2316 \cdot 1.4543 \cdot 1.0511 \cdot \sqrt{1.1}} = 1.41.$$

Thus, the suggested improved method improves the efficiency of tribotechnical tests by increasing the ability of the abrasive particles of SiC ~1.4 times. In the experimental studies (Fig. 12), it is manifested as an increased angle of the line inclination, which determines the loss of mass per unit of time due to the high exchange of the abrasive mass in the area of interaction between the working surface of the sample and the abrasive.

The undertaken tests show that the use of the improved method and the apparatus for testing materials for wear resistance under friction on a loose abrasive improves the efficiency of tribotechnical research by providing high abrasive ability of particles. This is due to the high level of abrasive mass exchange in the area of interaction between the working surface of the sample and the abrasive. The obtained analytical dependences allow accurate prediction of the magnitude of the material's wear by analyzing the shapes of abrasive particles.

A promising direction for future research is to expand the range of materials for studying the use of abrasives of different morphology to determine a correlation between the factors that affect the process of abrasive wear.

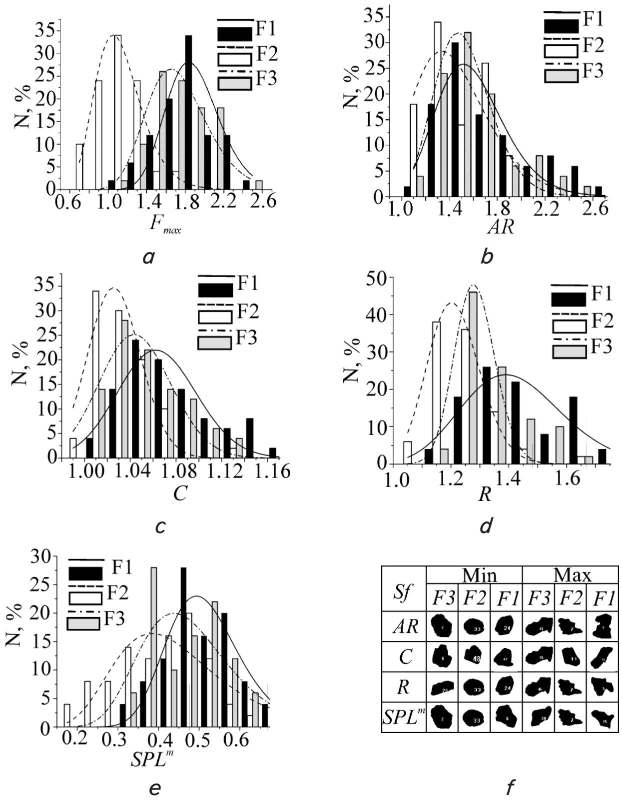

Fig. 10. The comparative statistical analysis of the frequency distribution of shape parameters of abrasive particles: *a* – the Feret diameter (F_{max}); *b* – the aspect ratio (AR); *c* – convexity (C); *d* – roundness (R); *e* – sharpness (SPL^m); *f* – extreme parameters

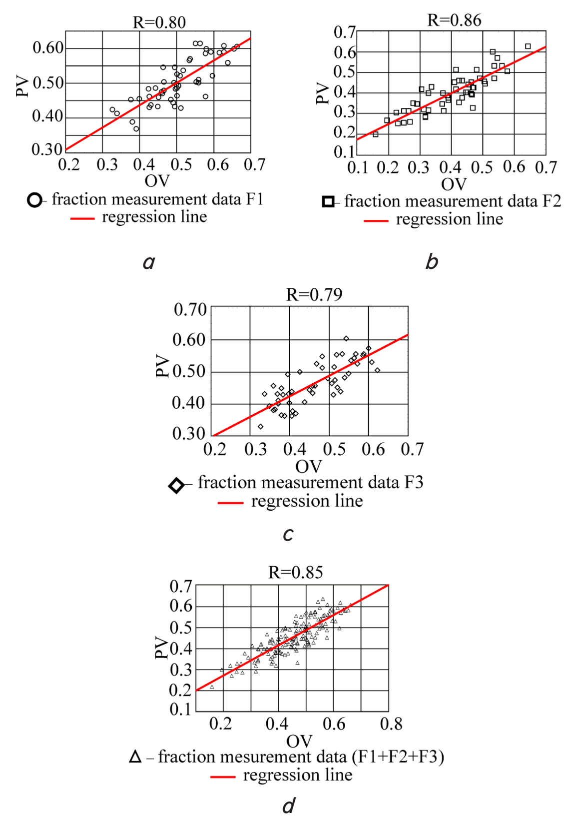

Fig. 11. The results of the regression analysis of correlations between the SPL^m parameter and the parameters R and C: *a* – F1; *b* – F2; *c* – F3; *d* – F1+F2+F3

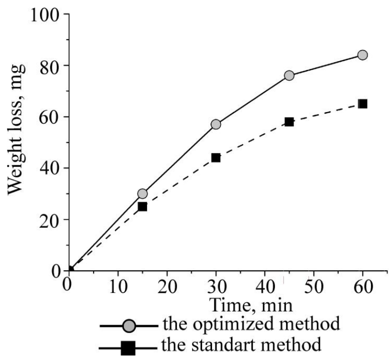

Fig. 12. The research results on wear resistance by the Lorentz force method and the optimized method (steel 40X material without heat treatment)

6. Conclusions

1. The method and the apparatus for determining the relative wear resistance of materials and coatings make it possible to test materials for abrasive wear by loose abrasives at a significant specific pressure of the abrasive and at a high abrasive mass exchange in the area of interaction between the working surface of the sample and the abrasive. The advantages of this method are manifested in the simplicity of its implementation as well as in the high accuracy and information content of the obtained test results.

2. The form of the abrasive particles of SiC that are used in tribotechnical tests are accurately approximated by a Fourier series, using elliptical descriptors for 50 harmonics obtained from the Freeman chain code. This makes it possible to present the contours of the particles in terms of functions and to calculate the parameter of the particle's sharpness SPL^m, which is in close correlation with the intensity of wear for abrasives of various shapes.

3. The results of the regression analysis have been developed in an equation to predict the wear rate of steel in terms of friction on a loose abrasive with known parameters of roundness (R), convexity (C), sharpness (SPL^m), and size (F_{max}) of abrasive particles.

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