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ON THE STUDY OF THE MECHANISM AND CRITERIA FOR MATERIAL WEAR RESISTANCE DURING ABRASIVE WEAR

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Abstract

This article investigates the mechanism and criteria for the wear resistance of materials during abrasive wear. The results of the conducted studies show that the $\tau_k - H$ and $\varepsilon - H$ dependencies coincide in their nature, indicating that τ_k and ε represent comparable characteristics of the material's strength properties. It was revealed that cutting stress (τ_k) is one of the indicators of the mechanical properties of a material's surface layer. The rectilinear nature of the $\varepsilon - \tau_k$ relationship allows for the recommendation of scratching stress (τ_k) as a criterion for evaluating resistance to abrasive wear.

Through the study of the abrasive wear mechanism, it was established that a portion of the metal involved in deformation is distributed as bulges along the scratch edges, while the remainder is removed in the form of micro-chips. A similar phenomenon is observed when scratching steels; the type of fracture depends on the material's hardness and the indenter load. The derived analytical relationship for determining cutting stress enables the selection of wear-resistant materials for manufacturing friction unit components at the design stage. It was found that assessing the mechanical properties of the surface layer by the scratching method provides a more accurate and comprehensive understanding of the potential wear resistance of materials during abrasive wear than indentation hardness.

Keywords: *abrasive wear, wear intensity, wear resistance, hardness, scratch method, shear stress.*

I. Introduction

Abrasive wear is the process of surface degradation caused by hard abrasive particles entering the sliding contact zone. In this scenario, a three-element "part-abrasive particle-part" (PAP) contact system forms between the working surfaces. Within the contact zone, abrasive particles create an intermediate layer. They participate in friction and transmit the applied load from one surface to another. This interaction generates a spectrum of stresses at the contact point, with their level, value, and direction depending on numerous factors. These factors include the abrasive's shape and size, its orientation relative to the rubbing surface, the hardness ratio between the abrasive and the material, and the applied load, among others.

Most researchers [1-8], based on their studies of the abrasive particle movement within the contact zone, note that depending on the aforementioned factors, these particles either roll, or they embed and become fixed in one of the surfaces. A fixed abrasive particle, by scratching the other contacting surface, subjects it to elastic or plastic deformation, or micro-cutting occurs.

According to I.V. Kragelsky [4], three types of interaction are possible, depending on the relative depth of abrasive penetration into the rubbing surface (h/ρ):

- Elastic compression,
- Plastic compression
- Micro-cutting

In this context, various relationships exist between a material's wear resistance and its mechanical

properties. For instance, in elastic deformation, wear resistance is dependent on the modulus of elasticity; in plastic deformation, it correlates with tensile elongation and hardness; and in micro-cutting, it is primarily influenced by hardness.

Analysis of previous research indicates that friction marks (scratches) caused by abrasive particles result from either metal compression or micro-cutting. In their investigations, M.M. Khrushchov and M.A. Babichev [1] demonstrated a proportional relationship between a material's wear resistance and its hardness.

Some researchers contend that a general wear law for materials should be analytically expressed as a function of various factors influencing either linear wear or wear rate [5,8]. However, deriving such a comprehensive relationship is exceptionally challenging due to the multiplicity of contributing factors. Concurrently, the theory of wear in machine components necessitates robust computational methods for evaluating wear in diverse types of joints operating under varying conditions.

From the foregoing, it follows that the developed computational method for addressing this problem possesses significant theoretical and practical relevance.

Research Objective. The aim of this work is to model a test setup and a calculation method for abrasive wear in a sliding friction pair, derive analytical expressions for comparative analyses, and ultimately determine a criterion for abrasive wear resistance.

Research Method. When studying the nature and patterns of abrasive wear, the proper selection of laboratory test equipment and methodology is crucial. The chosen setup must ensure that the nature of abrasive-surface contact accurately reflects the interaction occurring under real-world operating conditions.

It's understood that abrasive wear of materials results from the action of hard abrasive particles, whether in a free or bound state. Consequently, abrasive particles entering between rubbing surfaces either cut the metal, scratch it, or roll, forming compressed indentations in the surface layer.

Considering the aforementioned, recent laboratory studies aimed at addressing these challenges have increasingly utilized mathematical methods involving single abrasive scratching. This approach allows for the investigation of various factors influencing wear, the determination of surface layer mechanical properties, and the derivation of analytical expressions for comparative analyses and factor evaluation.

Solution Approach. During operation, abrasive particles entering the contact zone between working surfaces significantly alter the nature of layer interaction. By forming an intermediate layer, these abrasive particles separate the surfaces, hindering molecular interaction between materials and thereby reducing the risk of seizing. In this scenario, the abrasive particles disrupt the stable state of the frictional contact, leading to abrasive wear.

In laboratory settings, the single abrasive scratching method has been employed to evaluate the abrasive wear resistance of material surface layers. It should be noted that, in principle, any sufficiently precise mechanical setup with an indenter of a precisely known radius, capable of gradually indenting the material under test, can be considered suitable for determining the transition from one type of deformation to another during sliding. By progressively increasing the load and observing the interaction process, it's necessary to reach an indentation depth corresponding to the onset of metal sliding. To this end, an apparatus (device) allowing for scratching tests was developed and installed based on a desktop lathe to assess the wear resistance of material surface layers during abrasive wear. This setup comprises components for sample clamping, a scratching element (indenter), balancing, and measuring both the scratching force and indentation depth [6,10,12,13,15,16].

When conducting wear tests on metals in an abrasive environment, a crucial condition is to ensure that the primary parameters of the wear process precisely match the operational conditions. For machine working components, these parameters include the shape and hardness of abrasive particles, sliding velocity, and the pressure exerted by the abrasive on the rubbing surface. Quartz sands are the most commonly used abrasives, with their microhardness typically ranging from 10,000 to 11,000 MPa and particle sizes generally not exceeding 0.25 mm.

During the scratching process, it was hypothesized that the parameters of the indenter's scratching tip, which simulates an abrasive particle (specifically, the radius of curvature (ρ) and the apex angle (β)), would approximate those of real abrasive particle asperities. Furthermore, the applied load was intended to be close to the fracture force of abrasive particles. To achieve this, a series of tests [7-9] were conducted. Based on the obtained results, a corundum needle with a conical spherical tip was selected as the indenter, featuring $\rho = 30mkm$ and $\beta = 50°$. The applied load was determined to be F ≤5.5N. The microhardness of corundum typically ranges from 19,000 to 23,000 MPa.

Work [1] indicates a proportional relationship between the cutting resistance of metals and their hardness. It is assumed that there is a direct correlation between the resistance of steels to tensile fracture or their hardness and the cutting force.

To verify the validity of the aforementioned statement and to elucidate the influence of individual factors on the destruction process of the metal surface layer, relevant tests were conducted. The test and calculation results are presented in graphically in Figures 2-11. To minimize measurement errors during the tests, we applied several (primarily three) parallel scratches under the same test conditions by transversely moving the specimen using the machine's carriage. The depth of abrasive penetration was determined by measuring its average values in several (5-10) cross-sections, equally spaced along the entire length of the scratch, using a Linnik bifocal microscope at 270x magnification. Based on the test results obtained from specimens of varying hardness, the dependencies $F_x = \varphi(F_y)$ and $F_x = \varphi(h)$ are plotted in Figures 2 and 3, respectively. These relationships exhibit similar trends. For the same normal load F_y, F_x decreases as the material hardness increases (Figure 2). However, for the same abrasive penetration depth (h), F_x increases with increasing hardness (Figure 3). At small values of F_y and h, the difference between the scratching forces is negligible, gradually increasing as these values rise.

At various values of normal load (F_y) applied to the indenter, the nature of the dependence of the $\frac{F_x}{F_y}$ ratio on specimen hardness is approximately similar (Figure 4). As hardness increases, the $\frac{F_x}{F_y}$ ratio decreases. With an increase in load (F_y), the rate of decrease in the $\frac{F_x}{F_y}$ ratio intensifies. In our opinion, the primary reason for this lies in the alteration of internal stresses and the fracture characteristics of the surface layer, which arise from tempering the specimens at different temperatures after quenching. For the tested material within the specified hardness range, $\frac{F_x}{F_y}$ varies from 0.12 to 0.733.

Based on the analysis of experimental results and mathematical calculation methods, the following analytical expression was derived for determining the scratching force:

$$F_y = 0.8556\left(\frac{F_y^3}{2\pi\rho^2 H - F_y}\right)^{\frac{1}{2}} \tag{1}$$

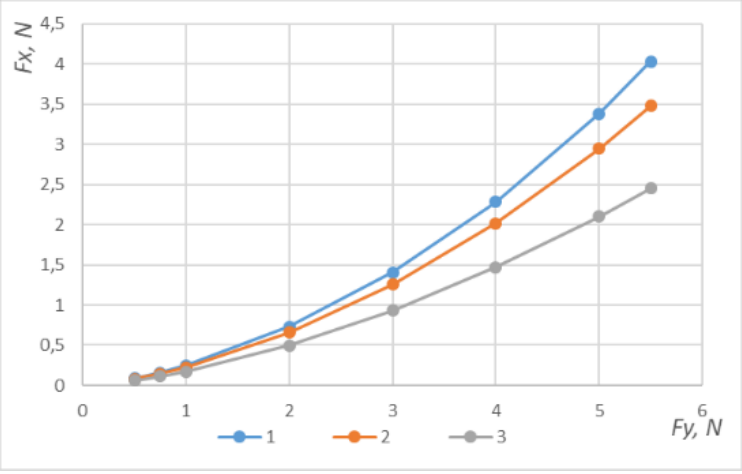

Figure 1: *Dependence of scratching force on the normal load applied to the indenter:* $1 - HB\ 2200 \dots 2400, 2 - HB\ 2550 \dots 2950, 3 - HRS\ 43 \dots 48$

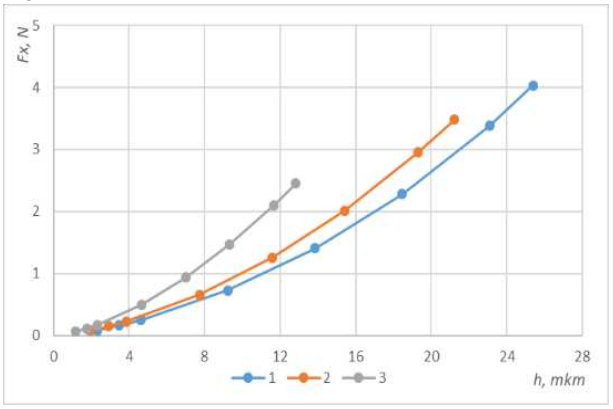

Figure 2. *Dependence of scratching force on abrasive penetration depth:* $1 - HB\ 2200 \dots 2400, 2 - HB\ 2550 \dots 2950, 3 - HRS\ 43 \dots 48$

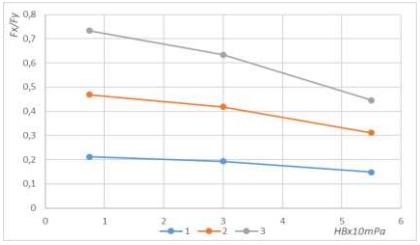

Figure 3. *Dependence of the ratio of scratching force* (F_x) *to vertical normal force* (F_y) *on the hardness* (HB) *of the tested material:* $1 - F_y = 0{,}75N;\ 2 - F_y = 3N;\ 3 - F_y = 5{,}5N$

2. CONCLUSIONS

Based on the test results, the main indicator of the mechanical properties of the surface layer – the specific scratching resistance force or conditional shear (cutting) stress – can be determined using the following formula.

$$\tau_x = \frac{F_x}{A} \tag{2}$$

Since the projection of the scratch's cross-section has the shape of a segment (Figure 1b).

$$A = \frac{2.015}{3} \cdot ah \tag{3}$$

Based on the scheme (Figure 1b), from ΔOO_1D we can write:

$$a = 2 \cdot O_1D = 2\sqrt{2\rho h - h^2} \tag{4}$$

If we substitute expression (3) into (2), taking into account formula (4), and perform certain transformations, we obtain:

$$\tau_x = \frac{F_x}{1.343h\sqrt{h(2\rho - h)}} \tag{5}$$

If we substitute formula (1) into formula (5) and consider that $h = \dfrac{F_y}{\pi\rho H}$ [4], performing certain transformations, we obtain:

$$\tau_k = \frac{6.28\rho^2 H^2}{6.28\rho^2 H - F_y} \tag{6}$$

From formula (5), it's evident that τ_K, which characterizes scratching resistance, is a stress both in terms of its unit of measurement and its meaning. It's primarily determined by the dimensions of the resulting scratch.

Figure 5 illustrates the dependence of the shear stress (τ_K) generated in the material's surface layer during scratching on the normal load (F_y) applied to the indenter $\left(\tau_x = 4\left(F_y\right)\right)$. As the graphs show, the nature of these dependencies is similar, regardless of the material's hardness. At low load values, the difference in shear stress values for materials of varying hardness is minor, but this difference increases with rising load. Based on the analysis of test results, it has been established that the fracture and surface mechanisms during abrasive wear are determined by the nature of both the metal and the abrasive material, as well as the conditions of interaction between abrasive particles and the metal surface. It was found that plastic deformation and micro-cutting are predominantly observed during abrasive wear. The prevalence of one of these fracture types depends on the material's hardness and the normal load applied to the abrasive. It was determined that when scratching low-hardness steel ($HB < 2300$), the prevalence of plastic deformation over micro-cutting persists up to high normal load values $\left(F_y = 5N\right)$. In contrast, with increasing hardness, this prevalence is observed at relatively low normal load values—for example, at $HB > 2500$, $F_y = 3N$; and at $HRC > 43$, $F_y = 0{,}5N$. Metallographic investigations of the scratch profile and bottom under a microscope reveal the distribution of a certain portion of the deformed metal along the scratch edges and its length, while the scratch bottom shows wave-like metallic displacements and spalling. These features were found to be characteristic of all tested steels of varying hardness.

Figures 6, 7, and 8 display the dependencies $\tau_k = \varphi\left(HB\right)$, $\varepsilon = \varphi\left(HB\right)$ and $\varepsilon = \varphi\left(\tau_k\right)$, respectively. As observed, these dependencies follow a linear relationship. However, the $\tau_k = \varphi\left(HB\right)$ and $\varepsilon = \varphi\left(HB\right)$ relationships do not pass through the origin (i.e., they intersect the ordinate axis), whereas the $\varepsilon = \varphi\left(\tau_k\right)$ dependency changes along a straight line that passes through the origin. Based on these observations, the following expressions can be written for these dependencies:

$$\tau_k = \tau_{k0} + C\left(H - H_0\right) \text{ (figure 5)} \tag{7}$$

$$\varepsilon = \varepsilon_0 + b\left(- H_0\right) \text{ (fiqure 6)} \tag{8}$$

$$\varepsilon = k\tau_k \text{ (figure 7)} \tag{9}$$

The values of these coefficients are equal to the tangent of the angle of inclination, $tg\alpha$, of the derived dependencies (straight lines) with respect to the abscissa axis. These values vary depending on the normal load applied to the indenter, as illustrated by the relationship. $\tau_k = \varphi(F_y)$.

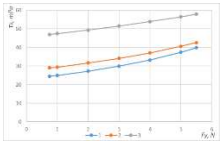

Figure 4. *Dependence of shear stress* $\boldsymbol{\tau_k}$*, arising in the surface layer during scratching, on the normal load* $\boldsymbol{F_y}$ *applied to the indenter:*

$1 - HB\ 2200 \ldots 2400, 2 - HB\ 2550 \ldots 2950, 3 - HRS\ 43 \ldots 48$

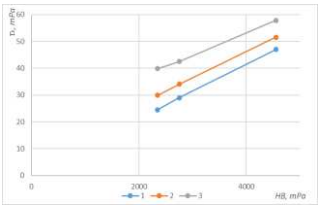

Figure 5. *Dependence of shear stress on hardness during scratching:* $o - F_y = 0{,}75N; x - F_y = 3{,}0N; \nabla - F_y = 5{,}5N$

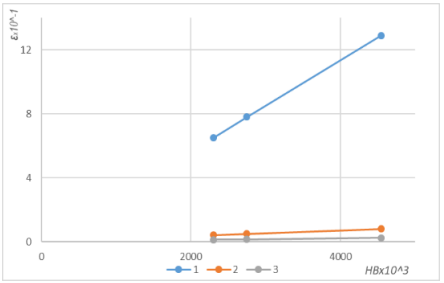

Figure 6. *Dependence of wear resistance on material hardness:* $1 - F_y = 0{,}75N; 2 - F_y = 3{,}0N; 3 - F_y = 5{,}5N$

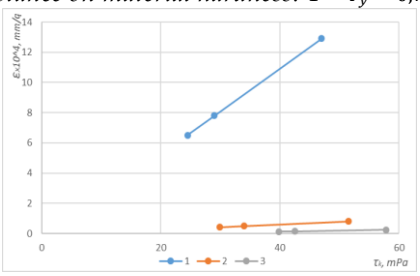

Figure 7. *Dependence of material wear resistance on shear stress generated during scratching:* $1 - HB\ 2200 \ldots 2400,\ 2 - HB\ 2550 \ldots 2950, 3 - HRS\ 43 \ldots 48$

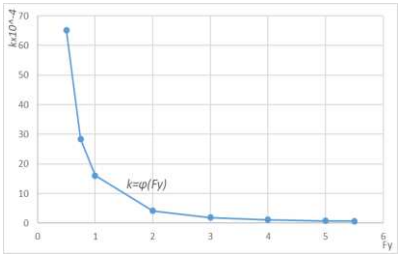

Figure 8. *Dependence of proportionality coefficient K on the normal force F_y applied to the indenter:*

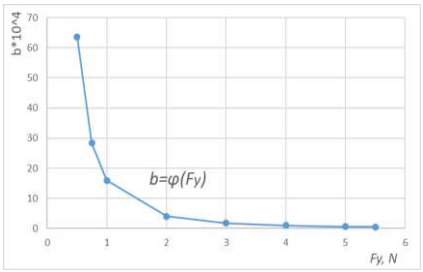

Figure 9. *Dependence of proportionality coefficient b on the normal load F_y applied to the indenter:*

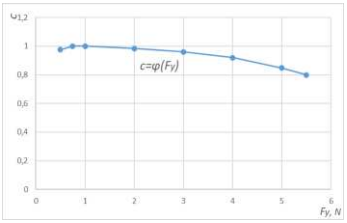

Figure 10. *Dependence of proportionality coefficient c on the normal load F_y applied to the indenter:*

The calculated proportionality coefficient values are presented in the graphs. From the values in the graphs, it's evident that these coefficients adopt varying magnitudes depending on the normal load F_y applied to the abrasive. To ascertain the nature of their variation, we plot the corresponding dependencies: $c = \varphi(F_y)$, $k = \varphi(F_y)$ and $b = \varphi(F_y)$ (Figures 9, 10, and 11). An analysis of the values in the graphs (Figures 9 and 10) reveals that the character of variation and the values of coefficients k and b as functions of F_y are very similar and fall within comparable ranges. Employing mathematical calculation methods, the following analytical expressions were derived for determining these coefficients:

$$c = F_y^{-0,1}; k \approx b = 16 \cdot 10^{-4} \cdot F_y^{-2} \quad (10)$$

Thus, the conducted research has established that a change in the mechanism of metal surface destruction does not alter the $\varepsilon - H$ dependency. This implies that, in various wear scenarios, wear resistance is determined by a single mechanical property of the metal. To identify this indicator, an attempt was made to analyze the dependencies of material hardness on several mechanical properties, and it was found that shear (cutting) resistance is the most suitable characteristic for this purpose.

Under real-world scratching conditions, micro-cutting with chip formation or metal sliding without particle (chip) detachment and structural failure are observed. When metals are scratched by single indentation, the hardness is proportional to the hardness determined by pyramid indentation [2,3,5,11,14,17,18,19]. From this, it's concluded that the scratching resistance of metal without chip removal and wear resistance during abrasive wear are comparable characteristics. However, the uncertainty of deformation during indenter indentation into the metal prevents verification of the similarity between scratching resistance and shear resistance. To clarify this position, the dependencies between shear resistance, which is related to wear resistance, and hardness were investigated. From the graphs (Figures 6, 7, and 8), it's also evident that the nature of the $\tau_k - H$, $\varepsilon - H$ and $\varepsilon - \tau_k$ dependencies coincides. For this reason, they are considered comparable characteristics of the mechanical properties of materials.

Thus, an analysis of literature data and our research indicates that assessing the mechanical properties of the surface layer using the single-abrasive scratching method, compared to hardness determined by indenter indentation, provides a more precise and comprehensive understanding of

the potential wear resistance of materials under abrasive wear. The foregoing confirms the value of the single-abrasive scratching method as a laboratory research technique for material properties and highlights the necessity for further advancements in sclerometry [20-25].

Both the linear relationship of the $\varepsilon - H$ and $\varepsilon - \tau_k$ dependencies and the correspondence of abrasive wear characteristics between laboratory and operational conditions suggest that shear stress, alongside hardness, can be effectively utilized as a primary mechanical property of the surface layer for wear resistance criteria.

In the above formulas:

A – the projected area of the scratch's cross-section onto a plane perpendicular to the scratching direction;

β – the apex angle;

c, b, k – proportionality coefficients.

F_x – the scratching resistance force, N;

F_y – the normal force, N;

H – the hardness of the heat-treated material;

H_o – hardness of the surface layer of the material that has not undergone heat treatment;

h – the depth of indenter penetration into the material; $a = ED$ – the chord length;

τ_k – the shear stress during cutting;

τ_{ko}, ε_o and H_o represent, respectively, the shear stress;

ρ – the radius of curvature of the indenter's scratching tip, mm;

ε_o – wear resistance; and

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