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Valerii Kosarchuk [1*], ***Mykola Chausov*** [2], ***Volodymyr Tverdomed*** [3]

[1] Professor, Theoretical and Applied Mechanics Department, State University of Infrastructure and Technologies, 9, Kyrylivska str., Kyiv, 04071, Ukraine. ORCID: https://orcid.org/0000-0003-2703-3542.

[2] Professor, Department of Mechanics, National University of Life and Environmental Sciences of Ukraine, 15, Heroiv Oborony str., 03041, Kyiv, Ukraine. ORCID: https://orcid.org/0000-0002-6790-6216.

[3] Assistant professor, Railway Track and Track Facilities Department, State University of Infrastructure and Technologies, 9, Kyrylivska str., Kyiv, 04071, Ukraine. ORCID: https://orcid.org/0000-0002-0695-1304.

[*] ***Correspondence***: tverdomed@gsuite.duit.edu.ua; kosarcuk_vv@gsuite.duit.edu.ua

Effective method of evaluating the level of material damage under different loading conditions

The article analyses the known experimental results of the assessment of the level of damage of structural materials of various grades under the conditions of long-term, cyclic, static loading, and lubricated friction. The structural changes that occur in the materials during loading have been shown with correlate to the changes in the statistical scattering characteristics of the hardness measurement results. This enables prediction of the kinetics of damage accumulation in materials during operation and, therefore, prediction of their service life. This approach is relevant for the development of methods for the assessment of the current condition and residual life of structures in the railway and other transport industries. It is proposed to use this methodology to evaluate the level of damage to the microstructure of materials in the contact zone and its impact on the tribological characteristics of metal friction pairs. A new method is proposed for the performance assessment of lubricating compositions based on industrial lubricants that contain nano-additives of different chemical compositions for higher wear resistance of heavy-loaded steel friction pairs. The method is based on the joint analysis of the experimental data on the wear kinetics, variation of the relative hardness, and level of damage in the surface layers of the metal friction pairs. The structural damage of the materials in the contact zone is determined by employing the statistical parameters of scattering of the hardness values. The methodology has been approved for steel friction pairs where lubricants based on industrial oil and on nano-additives of copper, magnesium alloy, graphite, and two grades of medium-carbon steels, are used.

Keywords: *hardness, rail–wheel pair, statistical data processing, lubricating composition, friction and wear testing, wear resistance, tribological characteristics, damages.*

Introduction. The determination of the current condition and residual life of the structural elements and parts of machinery is considered to be one of the key challenges in modern-day mechanical engineering, since the physical-mechanical properties of a material change in the process of operation and the estimated life may prove to be unreliable. The relevance of these challenges is even greater for the structures and parts of the machinery used in the energy and transport sectors. Determination of residual life is based on the theoretical and experimental methods of assessment of the level of material damage of the structure as a result of mechanical, thermal, or other actions. The theoretical assessment may employ the methods of continuum damage mechanics (CDM) based on the phenomenological growth models of scattered defects, i.e. pores and micro cracks. These models assume that the number of defects in the elementary volume of the material is high enough for CDM modeling of the growth processes thereof as this type of modeling views damage as an additional thermodynamic parameter.

Active research efforts are currently being made to develop these models [1–4]. Some of the models have already been used in modern software packages for strength calculations [5, 6]. However, all the theoretical models require experimental determination of the parameters and functions present in the defining relations. Here, the aspects of determination of specific physical mechanisms of the degradation process of material mechanical properties and practical methods for assessing the damage level and the nature of its change during the operation of the component, need to be considered. The relevance of these aspects is also associated with the development of methods to improve the wear resistance and reliability of friction assemblies, as the wear of components caused by friction is known to be one of the main causes of failure and breakdown of machine parts and structural elements, particularly in the energy and transport sectors.

In this context, the interpretation of the term “damage” is fairly ambiguous. In material mechanics, damage is related to a decrease in resistance to a certain mechanical load or other external action leading to an increase in the number of defects in the material. In contemporary physics, it has already been proven that the loss of durability resulting from the failure process is the final stage of defect accumulation at all structural levels of the material. Therefore, it is critical to identify and use a comprehensive measure of damage that would be fairly simple to determine by experiment. This would enable the researchers to employ damage as a specific parameter (scalar, tensor, function, or functional) during the determination of the relationships between the theories of inelastic deformation that take into account material damage.

Background analysis of the recent studies and definition of the problem. Various methods for the assessment of the level of material damage have already been proposed in a number of research studies. The methods could conditionally be classified as either destructive or non-destructive. The classification is conditional, as the same methods are used in both cases. A comprehensive analysis of the methods would require a separate publication; therefore, only a few of them are briefly reviewed in the present paper.

Most destructive methods imply performing tests on material specimens cut from certain areas of the structural component. The investigations of the mechanical behavior or structural condition of the cut specimens provide the characteristics of the current damage of the material, $\Pi(\mathrm{T}_i)$ where T_i represents certain parameters that characterise the level of operational load (e.g., time, passed tonnage, number of cycles, accumulated deformation, etc.). There is a certain initial damage Π_0 in any material; therefore, the same method is used for the determination of the damage level, while relative parameter $\frac{\Pi(\mathrm{T}_i)}{\Pi_0}$ is used for the analysis of damage kinetics. These methods include, in particular, weight measurement methods for the determination of material density; determination of the transverse strain coefficient and Young’s modulus defect during uniaxial tension or compression of specimens [7]. The methods help assess the degree of material loosening or volumetric deformation that characterizes its damage. In laboratory conditions, the results of damage level assessments under the above methods agree fairly well with each other [7]. The methods of quantitative metallography and fractography are used to analyze the geometric characteristics of the specimen failure surfaces and to determine the number of defects of various types [8,9]. It should be noted that the procedures for determining the degree of damage using these methods are quire labor-intensive, and the efforts are made to automate them [10]. Recently, the method of pushing out of the disc micro-specimens cut from large structural elements has become widespread as it helps minimize the appearance of new defects that might result from this operation. The investigations using these methods allow to assess the degree of material damage caused by mechanical, radiation, thermal, and corrosive actions on the structure by the means of measurement of certain characteristics of the mechanical properties of the material [11–13]. The level of defectiveness of the material specimens could be determined using other methods of structural investigation and technical diagnostics, such as acoustic emission, ultrasound, X-ray, electron microscopy, and others [14–19]. In certain cases, these methods are also used for in-situ diagnosing of the material damage of structures, predominately thin-walled ones, due to certain physical limitations of these methods. The latter techniques require the use of special and often costly equipment.

The most common method of assessing material condition is probably the hardness method, which has quite a few variants at present [20–25]. In general, hardness is considered to be the property of a material to resist the penetration of another, harder body (the indenter) into it. By its physical nature, hardness is assumed to be related to the mechanical characteristics of the material in the context of elastic-plastic deformation and failure.

The results of hardness measurement depend on the size, shape and material of the indenter; the method of application, value, and speed of the load; the capabilities of the equipment used for measuring the geometric parameters of impressions; the accuracy of calculation formulas, etc. In particular, as the load on the indenter decreases, the hardness indicators increase and the degree of the increase depends on the shape of the indenter. It should also be noted that most of mechanical characteristics are integral properties of the specimen of a certain shape, and the processes of restructuration of the microstructure on the surface versus those that take place in the middle of the specimen are different even at the stage of uniform deformation, let alone in the zones of its localization.

Currently, only approximate correlations between hardness indicators and some standard mechanical characteristics have been established [26, 27]. These correlations are considered purely empirical, since hardness is a local rather than an integral characteristic in relation to the sample size.

The simplest methods to measure hardness are the ball, pyramid, or cone indentation into a prepared surface of the part. These techniques are used to determine the macro-hardness of the material, as, contrary to micro-structure parameters, relatively large volumes of the material are subjected to deformation during the indentation. These methods are often used to assess the quality of parts after thermal treatment (e.g., rails and wheels of a rolling stock) [28, 29]. However, the methods are characterized by rather low sensitivity due to structural changes in the material arising from the accumulation of micro-defects [30–32].

Therefore, methods for determining micro-hardness are used for the quantitative and qualitative assessment of structural changes in the material. Determining micro-hardness as a notion implies a fairly large number of methods [22], which differ in the shape of the indenter, load application, and result recording techniques.

The micro-hardness methods are used to study the structural components of metals and alloys, analyze the anisotropy of mechanical properties of microcrystals, and to investigate changes in the mechanical properties of surface layers of parts caused by friction and wear, cavitation, corrosion, etc. The micro-hardness method has been found to be sensitive to changes in the phase composition of metastable materials, enabling the prediction of the kinetics of phase transformations under various conditions of thermo-mechanical loading of the parts made from this kind of materials [33]. This method is characterized by a fairly large scatter of micro-hardness indicator values, the main factors of which are the non-uniformity of the material, the measurement technique or the quality of specimen preparation, as changes in the surface micro-hardness are caused even by the mechanical cutting or grinding of the specimens. The dispersion of micro-hardness indicators largely depends on the indenter shape and value of the load acting on it, with the dispersion of data increasing at the decrease in the loading degree [22]. Nonetheless, the micro-hardness method is considered by many researchers to be a versatile method to investigate the mechanical properties of materials.

The neglect of the scale factor is a common weakness of all experimental methods for damage research using specimens made from the structural material. The damage accumulation process is very complex and takes place at all structural levels of the material. Hence, it depends on many factors, including the volume of the deformed material (this is related to the differences in the accumulation of elastic energy, conditions of dissipation of the thermal energy that builds up during deformation, statistical aspects of micro-defect distribution, etc.). Another factor is the complexity of modeling of the loading conditions of specimens in the experiment that would adequately represent the loading conditions of the structural material. In most structures, structural materials function under the conditions of non-uniform complex stress condition, and the transfer of research data from the laboratory to real structures should therefore be carried out with some caution.

The scatter in the mechanical properties of many materials is evidently associated with the specifics of their crystalline structure. Reducing errors associated with hardness measurement equipment and the so-called human factor (or an instrumental factor) and using modern automated testing devices could help establish correlations between certain characteristics of the structural state of the material and the parameters of the statistical law of distribution of the hardness measurement results.

Determining the nature of the scatter of mechanical properties of various structural materials and choosing adequate statistical laws for the mathematical description of experimental data has been a relevant problem in materials mechanics for many years. The need for research in this area is related to the necessity of accounting for the scatter of mechanical parameters used in the estimation of the strength and reliability of the structural elements. If the correspondence of the experimental data to a certain statistical distribution law is established, then the distribution parameters could be used to assess the level of damage in the structural material. At the same time, if certain criteria for assessing the value of these parameters are present, it would be possible to predict the durability of the structure and its residual service life.

Quantitative evaluation of a random homogeneous variable (for example, a certain characteristic X of the mechanical properties of a material, the value of which can be represented as a series $X_1, X_2, \ldots, X_n$ for control purposes n) is known to use dimensioned and dimensionless numerical characteristics, which have no direct relation to the form of the law of distribution of a random variable: arithmetic mean $\bar{X}=\frac{1}{n}\sum_{i=1}^{n} X_i$; dispersion $D=\frac{1}{n}\sum_{i=1}^{n}(X_i-\bar{X})^2$; standard deviation $S=\sqrt{\frac{1}{n-1}\sum_{i=1}^{n}(X_i-\bar{X})^2}$; coefficient of variation $v=\frac{S}{\bar{X}}\cdot 100\%$. Two more parameters, namely kurtosis $E=\frac{\frac{1}{n}\sum_{i=1}^{n}(X_i-\bar{X})^3}{S^3}$ and skewness $A=\frac{D}{S^4}-3$, provide additional information about the shape of the distribution curve.

The scatter of values of mechanical properties within the totality with a sufficiently large n (theoretically at $n \to \infty$) is subject to the law of probability distribution, which is determined by the distribution function. Any finite set of values of these characteristics is a so-called statistical sample from the totality and provides only approximate representation of its characteristics. This circumstance is one of the main challenges when choosing a distribution law for a limited number of observation results (in particular, in the case of labor-intensive and relatively costly mechanical tests). According to the long-term studies, the results of which have been published in hundreds of scientific papers (for example, in certain observational papers [34 – 36]), the characteristics of mechanical properties mainly obey the normal or log-normal (the case where the logarithms of a random value correspond to a normal distribution law) laws. According to paper [36], the normal law is preferable for description of the parameters such as hardness or conditional tensile strength, while the log-normal or a variant of type III exponential distribution (two-parameter Weibull distribution) is preferable for the yield strength, threshold narrowing, and elongation. For the assessment of results of cyclic tests on strength limit, the three-parameter Weibull law is preferable, while for data on crack propagation velocity, the log-normal distribution is recommended. It should be noted that these conclusions apply to a limited group of materials and loading conditions. Significantly fewer publications provide the results on the dispersion of test data under complex stress conditions taking into account the anisotropy of materials, structural and phase composition, etc.

For smaller statistical samples typical for mechanical testing, it is generally recommended to use log-normal distribution or the two-parameter Weibull distribution law, as the latter only provides positive values of a random parameter, corresponding to the physical concepts of characteristics of mechanical properties.

Structural reliability is evidently linked to the number of defects that arise during its operation. The overwhelming majority of studies note that kinetic curves of damage accumulation $\Pi(\mathrm{T}_i)$ are nonlinear functions of their arguments. For analytical approximation of these curves, the Avrami equation, which contains an exponential function of a certain type known as the sigmoidal function, is often used:

$$y(t) = 1 - exp(-kt^n) \tag{1}$$

where k, n—parameters that are easily available where the experimental data are presented in double log plot.

This equation was originally used to describe topochemical reactions, such as isothermal phase transformations in metastable materials. Later, it was found to also be applicable to the modeling of other processes associated with structural transformations, such as crystallization and recrystallization, polymerization, accumulation of corrosive damage, etc. Studies [33, 37] have shown that changes in the phase composition of metastable chrome-nickel steel under elastic-plastic deformation over a wide range of low temperatures, which could be described by a modified equation of type (1), correlate well with changes in the micro-hardness of the material.

In large-scale tests, the hardness value can be considered random. Assuming the scatter degree of values H is associated with the level of material damage $\Pi(\mathrm{T}_i)$ and changes depending on two physically substantiated conditions $\frac{\Pi(\mathrm{T}_i)}{\Pi_0} > 1$ and $\frac{\partial\Pi(\mathrm{T}_i)}{\partial(\mathrm{T}_i)} > 0$, in view of the above, it is reasonable to employ Weibull statistics with a distribution function as in (1). The Weibull distribution is often used in reliability theory (the weak-link model) and when describing the dispersion of certain characteristics of mechanical properties of materials and predicting the probability of brittle failure. A detailed analysis of the distribution, its mathematical justification, and other applications can be found in the book by H. Rinne [38].

For a two-parameter Weibull distribution, the probability coefficient $P(H)$ could be written down as follows:

$$P(H) = 1 - exp^{-\left(\frac{H}{k}\right)^m} \tag{2}$$

When the experimental data correspond to the theoretical distribution (2), then the parameters k, m could be determined by logarithmising both parts of the relationship (2) twice

$$m \cdot ln(H) - m \cdot ln(k) = ln[-ln(1-P)] = ln\left[ln\left(\frac{1}{P}\right)\right]. \tag{3}$$

In coordinates $y = ln[-ln(1-P)]$ or $y = ln\left[ln\left(\frac{1}{P}\right)\right]$ and $x = ln(H)$, this is a straight line with the slope coefficient

$$m = \frac{ln[-ln(1-P)]}{ln(H) - ln(k)} \tag{4}$$

Experimental data are plotted on the special probability plotting paper and the degree and nature of their dispersion relative to the theoretical line (3) are visually assessed. For a more precise estimation, the least squares method can be used.

In practice, due to the limited number of test results, a situation arises where the data only approximately correspond to the distribution (2), and there is certain dispersion of the data relative to the straight line (3). Currently, more than 20 approximate methods are known for the estimation of the values of the distribution parameters (2) [38]. To determine parameters k, m analytical, grapho-analytical, and numerical methods are used [38–40]. However, this paper does not focus on a detailed review and accuracy assessment. It should be noted, that a dedicated software is available for statistical calculations using the Weibull distribution [41, 42]. For the purpose of determination of the parameter in the further investigations, the methodology proposed by E.J. Gumbel [43] is used, as the damage accumulation method, developed by a team of researchers at the G.S. Pisarenko Institute for Problems of Strength of the National Academy of Sciences of Ukraine [44], has been used for the justification. The main idea behind the method is to determine a correlation between the statistical parameters, which are applicable to the estimation of the degree of scatter of hardness measurement results in large-scale tests, and the level of material damage of the structure. This method, which has been named as «LM-hardness method», was subsequently standardized in Ukraine [45]. According to this method, the results of n measurements of material hardness are presented as a series $lgX_1, lgX_2, \ldots, lgX_n$, and the shape parameter m is determined by formula

$$m = 0{,}4343\ d(n)\left[\frac{1}{n-1}\sum_{i=1}^{n}(lgX_i - lg\bar{X})^2\right]^{-\frac{1}{2}} \tag{5}$$

Since the average value of a random parameter can be determined based on a number of observations n (i.e., for any sample), it therefore depends on n; consequently, relationship (5) contains function $d(n)$ referred to as the standard deviation [43]. The values of this function were calculated by the Computational Laboratory of Columbia University and are provided in certain statistical guides. To generate the totality $d(n) \to \frac{\pi}{\sqrt{6}}$, if $n \to \infty$. The increase in data dispersion and the corresponding decrease in parameter m indicates an increase in material non-uniformity (therefore, in some works, this parameter is referred to as the homogeneity parameter). A higher value of the homogeneity coefficient corresponds to a low level of dispersion of micro-hardness characteristics and, accordingly, a better organization of the microstructure of the surface layers of the material.

It should be noted that a change in the structural state of the material is not necessarily a sign of its damage, i.e., a deterioration of certain operational properties.

The analysis of distribution parameters above shall be preceded by a procedure of elimination of gross measurement errors. In the standard mentioned above [45], a methodology based on the use of the Smirnov criterion is used for this purpose.

Experimental justification of the LM-hardness method. To substantiate the ideas outlined above, some results available in the literature and provided by the experiments on the specimens made from structural materials of different grades are reviewed. Primarily, it should be noted that the data of this kind are scarce and are not systematically organized. Due to the limited volume of the article and some important issues related to corrosion damage of various kinds and damage to welded structures, the present paper does not consider any examples of diagnosing real structures. The authors of the paper have anticipated to address these issues in subsequent publications.

The change in material hardness under tensile test conditions was used to assess the damage degree D in paper [20]: $D = 1 - \frac{\tilde{H}}{H}\frac{\sigma_y}{\sigma_u}$, where H—hardness of the conditionally undamaged material (measured on the specimen before reaching yield strength σ_y), $\tilde{H}$—hardness of the most damaged material (measured on the specimen in the zone of deformation localization upon reaching the conditional failure threshold σ_u). It was assumed that the initial hardness and yield strength had a linear relationship.

In paper [46], an attempt was made to directly link the level of material damage to the degree of dispersion of standard mechanical characteristics (elasticity modulus, yield strength, Poisson's ratio, conditional strength limit), which was estimated by the value of the parameter m using formula (5). In tensile experiments, identical specimens of the length equal to five diameters, made from chromium steel (40X) and high-strength aluminum alloy (B95), were used. The impact of "instrumental" errors was minimized to a certain extent by providing identical experimental conditions, careful specimen selection, and control of the measurement of forces and deformations. As a result, the obtained data did not contain any systematic outliers (anomalous observations). The level of deformation was used as a development parameter. According to the test results, there was no correlation between the damage levels calculated on the basis of the scatter of mechanical characteristics. Furthermore, the damage level was the transition highest at the stage from elastic to elastic-plastic deformation, and as deformation increased further, the rate of accumulation of damage accumulation decreased.

This fact is considered in greater detail below, and an attempt is made by the authors to explain it, as similar results were obtained in other experiments.

In certain studies, the correlation coefficient υ was used as a parameter to evaluate the hardness data dispersion [47, 48]. Study [47] provides data (Fig. 1) on the level of threshold damage and the average hardness of two-phase $(\alpha + \beta)$ alloy VT6 (Ti-6Al-4V) during the static long-term strength tests under uniaxial tension conditions at $\sigma = const$. Dependency $\upsilon(\sigma)$ was found to be close to linear. Assuming that long-term strength decreases at an increase in the load value, this is obviously associated with greater damage in the material and, consequently, with an increase in the number of microstructural defects. This leads to a larger dispersion of micro-hardness values, as evidenced by the increase in the variation coefficient. At the same time, the average hardness (expected value) hardly changes. This indicates a lack of correlation between the scatter level of the hardness values and its average value.

Qualitatively similar dependencies were obtained by the authors of study [48] under the condition of cyclic pulsating loads at 0.3 Hz frequency on the specimens of heat-resistant steel 10GN2MFA (10ГН2МФА) commonly used in nuclear power sector (Fig. 2).

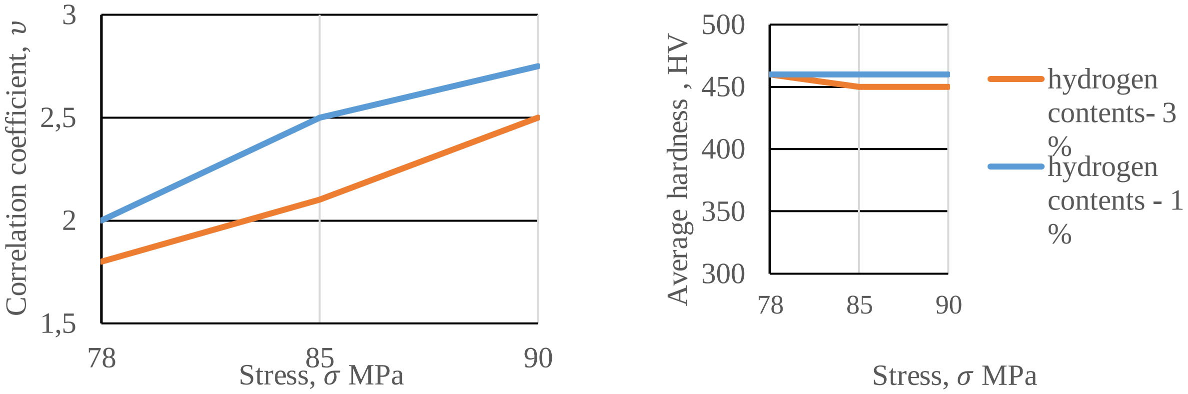

Fig. 1. **Dependence of the correlation coefficient and on the stress level at different hydrogen contents.**

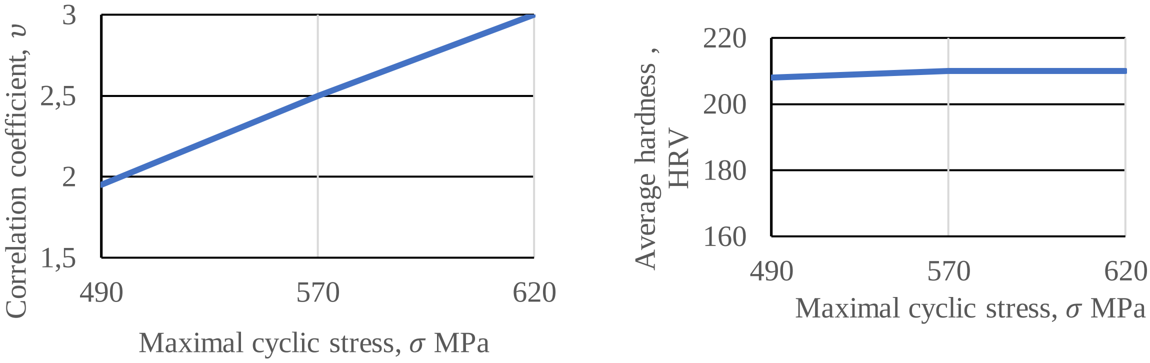

Fig. 2. **Dependence of the correlation coefficient and average hardness on the maximal cyclic stress levels.**

The results confirmed the presence of linear correlation between the maximum cyclic stress and the level of material damage, which was evaluated based on homogeneity parameter m, while hardness was determined in the zone of appearance of the first fatigue crack. This experiments also demonstrated that the previous impulse load affected the type of correlation, since the phase composition would change under the conditions of dynamic unbalanced processes, resulting in the physical and mechanical properties of materials. It has been concluded by the authors of the present paper that, in the absence of phase transformations, the homogeneity parameter could be used in structural-mechanical models for the assessment of cyclic durability.

The presented data provide evidence of validity of the main rationale behind the method, namely, that the dispersion of hardness measurement results increases with the increase in the operating time parameter. In the studies referred to above, the value of stresses was used for the latter, while dependencies $\upsilon(\sigma)$ and $m(\sigma)$ were close to linear for the studied load modes. It should be noted that, despite the difference in physical processes of damage accumulation for these loading processes (long-term and cyclic), there are certain similarities in terms of damage accumulation occurring in the surface layers of the specimens, where cracks subsequently appear. A large number of microdefects leads to a significant increase in the correlation coefficient, which, in turn, indicates a decrease in the accuracy of determination of the parameters of statistical distribution. Regrettably, studies [47, 48] do not provide any data on the initial damage in the specimens, since it would require operating with relative values of the correlation coefficient in order to assess the degree of material damage.

An investigation [49] was conducted and provided results (Fig. 3) on the processes of damage accumulation in aluminum alloys D16ChATW and 2024-T351 under cyclic loading conditions (at 110 Hz frequency and 0.1 cyclic asymmetry coefficient).

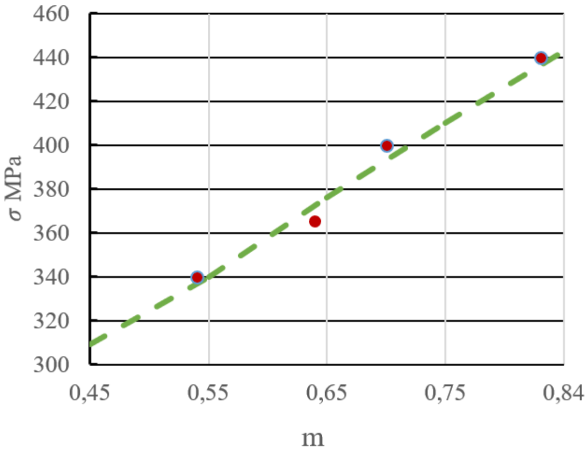

Fig. 3. **Dependence of the damage level on the maximal cyclic stress.**

It should be noted that the stress value is not a definitive estimate of the level of operating life of the respective loading modes. This is due to the potential accumulation of equivalent parameters at the long-term load, creep deformation, or time to failure, while under cyclic loading, the number of cycles to failure or cracking have the potential to accumulate.

In study [50], the results of investigation of micro-hardness distribution using the specimens made of different grades of structural materials (steel 45, steel 20K, steel 12Cr18N10T (12X18H10T), aluminum alloy D16T (Д16T) are presented according to the following test procedure: loading to the specified value of axial deformation; hardness measurement in 30 points of specimens; unloading of the specimen, registration of residual deformation, and repeated measurement of hardness.

Each material was subjected to four stages of testing, with the maximum deformation reaching approximately 1%. The evaluation of hardness measurement results was performed based on homogeneity parameter m (see (5)). The results of the experiments have suggested that the dispersion of hardness data is greater in a loaded state versus an unloaded state.

The results of evaluation of the scatter of hardness values in unloaded specimens presents on Fig. 4. The graphs are based on the data by study [50].

The degree of data dispersion clearly does not depend on the nature of strain hardening of the material when such an assessment is performed using the relative indicator $\frac{m}{m_0}$, where m_0 – value of homogeneity parameter m for the undeformed state of the material. It is noteworthy that for all the investigated materials, the greatest changes in indicator $\frac{m}{m_0}$ occurred at very small deformations, in the transition zone from elastic to elastic-plastic deformation.

The type of stress state also strongly influences the characteristics of the scatter of measurement results of micro-hardness for the specimens made from different materials. Study [51] has provided data from the experiments on thin-walled tubular specimens made of steel 45, copper M1, aluminum alloy D16T(Д16T), and stainless steel 12Cr18N10T (12X18H10T) under conditions of uniaxial tension, compression, and torsion (Fig. 5). The materials differed by nature of strain hardening, with the greatest hardening observed in medium carbon steel 45, the lowest – in copper M1. For all the investigated materials, the greatest scatter in hardness data was observed during torsion, while the lowest – during compression, and the difference value was influenced by the nature of strain hardening of the material. At the same time, there were hardly any changes in the average value.

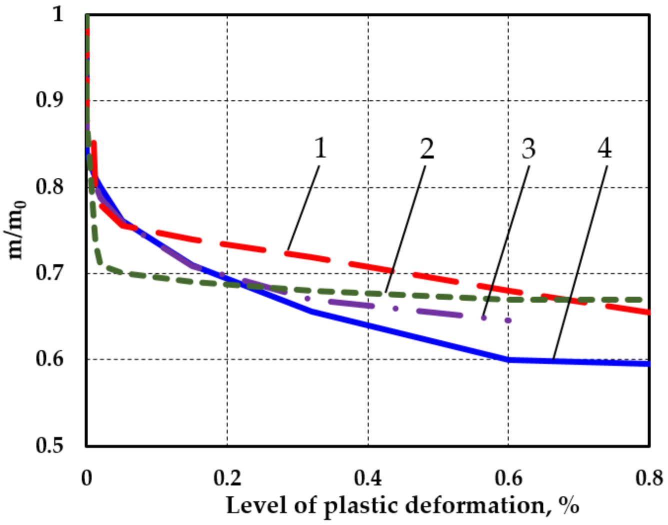

Fig. 4. **Dependency between the degree of dispersion of hardness data and the level of plastic deformation (1—steel 12Cr18N10T (12X18H10T), 2—steel 20K, 3—aluminum alloy D16T (Д16T); 4—steel 45).**

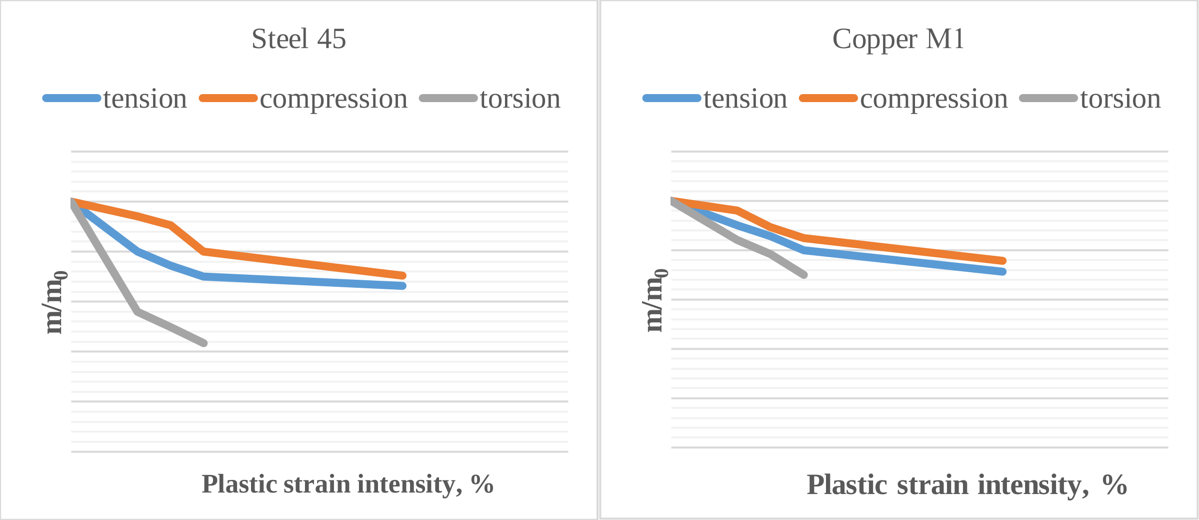

Fig. 5. **Dependence of the homogeneity coefficient on the level of plastic deformation.**

The main conclusion drawn from the experimental data analysis was that the scatter of the material hardness changed under the influence of any energy impact that led to structural changes in the material. However, the average hardness value changed insignificantly if there were no phase transformations or no changes in chemical composition or density of the surface layers of the material during thermo-mechanical loading.

Various types of thermal treatment are known to cause alterations in the mechanical properties of a material, including hardness. The degree of dispersion of micro-hardness data also depends on the heat treatment mode due to the change in the size of crystallites, development of residual stresses, potential emergence of new phases with different mechanical properties, etc. In view of the numerous factors that may influence the nature of hardness data scatter, establishing a definitive relationship between the heat treatment mode and the parameters of statistical distribution would currently be challenging.

During static deformation of metallic materials caused by the heterogeneity of the crystalline structure and presence of initial defects, certain microstructural changes occur as early as during the elastic deformation stage (dislocation movement, point defects, atom movement along grain boundaries, etc.), accompanied by the appearance of plastic deformations in individual grains. The intensity of these processes depends on the initial homogeneity of the material, presence of phases with different mechanical properties, various inclusions, grain size distribution, etc. According to the experimental data and numerical simulation results, plastic deformation begins in stress concentration zones of the surface layers of the material as they are characterized by the lowest shear strength. Surface stress concentrators generate the deformation defects (dislocations, disclinations, meso-localized shear strain bands, point defects) on the surface of the specimen that subsequently propagate into its deeper layers, leading to the development of plastic deformation throughout the specimen volume.

As a result, the scatter of hardness in the elastic region increases, and the dependence of the homogeneity parameter on stress becomes close to linear (see Fig.4). Upon reaching its conditional yield strength σ_{ys}, the material becomes more homogeneous, as a large portion of the grains have already transitioned into a plastic state. Hence, the dispersion of micro-hardness decreases, and damage accumulation in the material slows down. This process of structural changes in the initial stage of material deformation should be considered when modeling damage accumulation processes in real structures.

Significant changes in the correlation coefficient or homogeneity parameter occur under cyclic and long-term loading conditions at low stress levels. Under these kinds of loading modes, damage accumulation also occurs primarily in the surface layers of the material. If the stress level does not exceed the static yield strength, a strong linear correlation is present between the statistical parameters of the micro-hardness data scatter and the level of maximum stresses. The nature of this relationship $v(\sigma)$ and $m(\sigma)$ is evidently influenced by the type of stress state and temperature.

Method for the performance assessment of lubricating compositions. One of the factors that affect the performance and service life of machine components is wear of the contact surfaces due to friction. The wear process of the friction surfaces is quite complex, and its intensity depends not only on the shape and nature of the mechanical interaction between the friction components. This process is affected by a variety of other factors, which can sometimes be challenging to formalize, such as the presence of moisture, dust, lubrication regime, lubricant type, etc. Therefore, the possibilities for a theoretical solution of this problem, for example, by mathematical modeling of the contact interaction between friction pair components, are quite limited.

Local plastic deformation is known to potentially cause changes in the hardness of the surface layers of components during the friction process of rough surfaces. This phenomenon is directly related to the intensity of wear. However, stable correlations between these processes have not yet been established, as experimental data are not available or have not been systematized [52]. The contact interaction of solid rough bodies is characterized by discreteness and stochastic distribution of surface forces and heat sources, as well as high gradients of stress, strain, and temperature. As a result, surface layers of the material have a high concentration of defects in the crystalline structure and exhibit specific phase transformations that are often accompanied by changes in chemical composition. Meanwhile, the presence of lubrication, additives, and lubricating materials in the contact zone significantly influences the course of these processes.

In view of the damages primarily to the surface layers of the material in the case of sliding friction, it would be reasonable to assume that the degree of their damage could be determined by referring to the degree of hardness dispersion. Specific correlation relationships can be established by a combined analysis of data on wear intensity, changes in surface hardness of the specimens, and parameters characterizing the level of structural damage to the material.

To improve the operational properties of traditional lubricants used for lubricating rails and wheels of a rolling stock, various additives have been used recently, in particular, additives containing various nano-materials. The introduction of this kind of lubricating compositions into the friction zone can fundamentally change the nature and intensity of the processes of friction, wear, and defect formation. Natural metal-containing compounds (serpentine, dolomite, magnetite, aluminosilicates, etc.), polyvalent metal salts of fatty acids, nano-powders of various metals and alloys, as well as carbon-based materials of natural or artificial origin (graphite, diamond, graphene) are used as nano-additives. At present, there is no single opinion on the composition and method of manufacturing lubricants containing nano-additives, as their performance depends on the type of friction pair, operating conditions of tribounit, compatibility of lubricating materials and parts, etc. Therefore, performance assessment of a lubricant for improvement of the tribological characteristics of friction pairs should be based not only on the results of laboratory research but also on data from field experiments. However, in the case of wheel-rail friction pairs, the possibility of conducting field experiments is extremely limited due to a certain uncertainty in the conditions of power loads, the environmental impact, long duration, and the cost of work. Therefore, the choice of a specific lubricant from a variety of options should be made at the stage of laboratory research. One of the objectives of these experiments was to develop a method for performance assessment of a lubricant based on a combined analysis of data on changes in the main tribological (wear and friction coefficient) and strength (hardness value and damage parameter) characteristics during the experiment.

The choice of criteria for performance assessment of lubricants should be based on the assessment of the operating conditions of a specific friction pair. For many types of tribounit, the effect of a significantly increasing wear resistance is achieved only if there is a simultaneous significant reduction in the friction coefficient. Therefore, in practice, a simplified approach to the performance assessment of different types of lubricants is often used. Namely, a high-performing lubricant is considered to be one that provides a minimum friction coefficient and maximum stability of the lubricating film under certain temperature-force operating conditions of the friction pair. However, the value of the friction coefficient changes during operation/experiment as a result of deformations of the microrelief and damage accumulation, changes in temperature and physical-mechanical properties of the lubricating material and materials of the friction pair components.

The study [53] presents the results of hardness measurement and assessment of the level of damage to the surface layers of the specimens made of two grades of medium carbon steel. The experiment was conducted under sliding friction conditions using lubricating materials based on industrial lubricants with nano-additives of different chemical compositions. Application of this kind of lubricating compositions provides the possibility to control the tribological processes occurring in the friction zone to a certain extent. Therefore, one of the objectives of these experiments was to evaluate the effectiveness of lubricating compositions with nano-additives of different chemical compositions for improvement of wear resistance of steel friction pairs.

The shape of specimen, loading method and modes, measuring equipment, chemical composition of the steels and nano-materials, manufacturing method of nano-powders, as well as other details of the experiment, are thoroughly described in [53]. Average hardness $\bar{H}=\frac{1}{n}\sum_{i=1}^{n} H_i$ of the working surface of the specimens was determined based on the results of 30 measurements, in this case $d = 1.1124$. To assess the damage according to the methodology in [45], the hardness measurement data were presented as a series $lgH_1, lgH_2, \dots, lgH_n$, and according to the Smirnov criterion, these data were checked for gross measurement errors [45]. The average value of the series members $lg\bar{H}=\frac{1}{n}\sum_{i=1}^{n} lgH_i$ and the mean squared deviation were determined by $S = \sqrt{\frac{1}{n-1}\sum_{i=1}^{n}\left(lgH_i - lg\bar{H}\right)^2}$. The level of material damage was evaluated based on the homogeneity parameter by using formula (5), with an accuracy m of ±0.05.

The results were presented in relative values: $\Delta H = \frac{\bar{H}-\bar{H}_0}{\bar{H}_0}\cdot 100\%$ and $\Delta m = \frac{m_0-m}{m_0}\cdot 100\%$, where index 0 corresponded to the initial (conditionally undamaged) state of the material.

Table 1 presents the main results of the experiments for different friction modes using lubricating materials based on Greaseline Lithium BIO Rail 000 industrial oil and nano-additives of copper grade

M2, magnesium alloy grade MA2, graphite grade GK-1, steel 20, and rail steel. Powdered nano-additives, particle size 100 to 300 nm were obtained by electro erosion dispersion [53].

Table 1. **Key results of the experiment.**

Specimen material	Friction mode, lubricating composition number	Maximum wear	Relative friction coefficient	Change of mean hardness	Change of homogeneity coefficient
		Δh, mm	f/f_0	ΔH, %	Δm, %
Rail steel	No. 1, pure oil	0.08	$\frac{0.7}{1.39}$	+9.8	+31
	No. 2, oil + rail steel powder	<0.001	$\frac{0.84}{0.87}$	+14.7	+29
Steel 20	No 3, pure oil	0.095	$\frac{0.92}{0.6}$	+13.9	+34
	No. 4, oil + powder GK-1 (ГК-1)	0.084	$\frac{0.91}{0.8}$	+1.3	+58
	No. 5, oil + powder M2	0.23	$\frac{0.91}{1.15}$	+4.2	+63
	No. 6, oil + powder MA2	0.0015	$\frac{0.92}{0.72}$	+31.6	+32
	No. 7, oil + steel powder 20	0.001	$\frac{0.9}{0.73}$	+16.4	+32

The coefficient of friction f (KOF) is an important indicator of the performance of friction pairs, with its value significantly affecting the energy efficiency of machines and mechanisms. A decreasing friction in the contact areas would evidently be expected to a decrease in wear. However, this pattern mat be influenced by nano-additives. For different specimens, initial values f were slightly varied, which could be attributed to the presence of undeformed particles of nano-additives and possible differences in the surface roughness of the specimens. Therefore, for the purpose of analysis of the influence of different additives on the change in KOF, the experimental data are presented in Table 1 depicting relative values f/f_0, where f_0 represents the initial value of KOF, and f – its values after 1 (upper value) and 3 (lower value) hours of operation.

According to Table 1, the greatest increase in average hardness, the lowest damage level, and the least wear were recorded for lubricating compositions No. 2, No. 6, and No. 7. This signals that these lubricating compounds possess certain corrective properties. Lubricating compositions No. 2 and No. 7 are produced on the basis of an industrial lubricant with additives of steel nano-powders used for friction tests. In these cases, the additives to lubricating materials do not further affect the oxidation of the specimen surfaces, unlike the magnesium alloy additive used in composition No. 6. Magnesium, as the main component of this additive, oxidizes due to high electrochemical potential relative to iron. Therefore, the properties of this kind of a lubricating compound are inherently unstable. Moreover, under the experimental conditions under consideration, the composition containing magnesium alloy as an additive provides a friction coefficient that is too low for lubricating wheels and rails.

Lubricating composition No. 2 has the best set of properties. It is based on industrial lubricant with the addition of rail steel nano-powder. It provides a moderate increase in hardness and minimal surface damage, virtually no wear, and an optimal friction coefficient value. In addition, this nano-additive is non-toxic, provides the lubricant with corrective properties, and cost moderately, since it can be produced from scrap metal resulting from the mechanical processing of rails. Hence, it can be recommended for lubricating rails and wheels of railway rolling stock.

Conclusions. In this study has investigated a prospective method of qualitative and quantitative assessment of lubricants containing nano-additives of different chemical compositions to improve the wear resistance of steel friction pairs. The method involves an aggregate analysis and kinetics of damage accumulation during the change of mechanical and tribological characteristics in the course of friction, and the parameters are used to assess the level of material damage and the statistical distribution of hardness measurement results during mass tests. In particular, the correlation coefficient and the Weibull distribution shape parameter could be used as these statistical parameters.

An analysis of published works on the application of this method to assess the level of damage of structural materials of different grades has been carried out under static, cyclic, and long-term loads, as well as under friction conditions.

It has been demonstrated that, in cases of long-term, cyclic, and static loads, the degree of hardness data dispersion increases, thereby reducing the non-uniformity of the structure associated with material damage. An important conclusion from the analysis of the experimental data is the absence of correlation between the statistical parameters that characterize the scattering of hardness values and the average hardness value. Therefore, the average hardness cannot be considered a reference parameter for assessing damage. Furthermore, in view of multicycle the conditions of uniaxial loads and long-term loads, when the surface layers of the material are most damaged, the value of damage is proportional to the maximum stress. This indicates the possibility of using linear damage accumulation models under these kind of load conditions. It has also been shown that the kinetics of the damage accumulation process largely depends on the type of stress state.

The joined analysis of statistical characteristics of metal hardness scatter of friction pairs with the change in tribological characteristics during friction has allowed the authors of the present paper to evaluate the efficiency of lubricants with nano-additives of various chemical compositions. The proposed method allows identifying the corrective properties of lubricants with nano-additives at the laboratory research phase.

The method of this kind of comprehensive analysis, presented in this work, may be useful for an express assessment of the impact of lubricating materials on the wear resistance of friction pairs**.**

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Валерій Косарчук[1*], Микола Чаусов[2], Володимир Твердомед[3]

[1] Професор, Кафедра теоретичної та прикладної механіки, Державний університет інфраструктури та технологій, вул. Кирилівська, 9, м. Київ, 04071, Україна. ORCID: https://orcid.org/0000-0003-2703-3542.

[2] Професор, Кафедра механіки, Національний університет біоресурсів і природокористування України, вул. Героїв Оборони,15, м. Київ, 03041, Україна. ORCID: https://orcid.org/0000-0002-6790-6216.

[3] Доцент, Кафедра залізничної колії та колійного господарства, Державний університет інфраструктури та технологій, вул. Кирилівська, 9, м. Київ, 04071. Україна. ORCID: https://orcid.org/0000-0002-0695-1304.

Ефективний метод оцінки рівня пошкодження матеріалу За різних умов експлуатації

У статті проаналізовано відомі експериментальні результати оцінки ступеню пошкодження конструкційних матеріалів різних марок за умов довготривалого, циклічного, статичного навантаження та мастильного тертя. Показано, що структурні зміни, які відбуваються в матеріалах під час навантаження, корелюють зі змінами статистичних характеристик розсіювання результатів вимірювання твердості. Це дозволяє прогнозувати кінетику накопичення пошкоджень у матеріалах під час експлуатації, а отже, прогнозувати термін їх служби. Такий підхід є актуальним для розробки методів оцінки поточного стану та залишкового ресурсу конструкцій залізничного та інших транспортних галузей. Запропоновано використовувати цю методику для оцінки рівня пошкодження мікроструктури матеріалів у зоні контакту та його впливу на трибологічні характеристики металевих пар тертя. Запропоновано новий метод оцінки ефективності мастильних композицій на основі промислових мастил, які містять нанодобавки різного хімічного складу для підвищення зносостійкості сталевих важконавантажених пар тертя. Метод базується на спільному аналізі експериментальних даних щодо кінетики зношування, зміни відносної твердості та рівня пошкодженості поверхневих шарів металів пар тертя. Порушення структури матеріалів у зоні *контакту визначають за допомогою статистичних параметрів розсіювання значень твердості. Методика апробована для сталевих пар тертя, де використовуються мастильні матеріали на основі індустріального масла та нанодобавок міді, магнієвих сплавів, графіту та двох марок середньовуглецевих сталей.*

Ключові слова: *твердість, пара рейка–колесо, статистична обробка даних, мастильний склад, випробування на тертя та зношування, зносостійкість, трибологічні характеристики, пошкодження.*