

S. KOVALEVSKYY

MAGNETIC-RESONANCE AMORPHIZATION OF CONTACT KINEMATIC PAIR MATERIALS

In modern mechanical engineering, the requirements for the reliability and durability of components are constantly increasing, especially for those operating under intensive friction and high contact pressures. Traditional methods for improving wear resistance, such as alloying, coating applications, or heat treatment, often prove insufficiently effective or have limitations in terms of control and uniformity of surface modification. This article presents an innovative approach to surface-layer modification of materials—magnetic-resonance treatment—which enables the formation of unique microstructures, including partial amorphization, directly in the contact zone during operation. The aim of the study is the experimental justification of the application of magnetic-resonance treatment for the formation of an amorphous phase in the surface layers of materials in contact kinematic pairs to significantly enhance their wear resistance. The work thoroughly examines the theoretical foundations and analyzes current scientific research in the field of surface modification and the influence of strong physical fields on material structure and properties. Special attention is paid to phenomena of self-organization and phase transformations occurring under friction under the influence of magnetic fields. Experimental studies were carried out on D2 steel specimens subjected to magnetic-resonance treatment on a specialized rig. Friction and wear tests showed a significant reduction in the coefficient of friction (to 0.022–0.026) and wear intensity (by 3–4 times), indicating the formation of super-hard and super-plastic amorphous regions on the surface. Microstructural analysis by electron microscopy and X-ray diffraction confirmed the formation of martensitic phase and amorphous zones, as well as the reduction of crystallite size to the nanoscale in the contact zone. It is substantiated that these structural changes, induced by the resonant influence of a strong magnetic field, are the key factor in improving tribological characteristics. The obtained results demonstrate the high efficiency of the proposed magnetic-resonance treatment method. It was established that, under the influence of strong magnetic fields, amorphous and nanocrystalline structures form on friction surfaces, fundamentally altering the mechanisms of surface interaction, minimizing adhesive and abrasive wear. This confirms the hypothesis of the possibility of directed amorphization of materials to enhance their operational resilience. The practical significance of the study lies in the development of a new, environmentally friendly, and energy-efficient method for increasing the service life of machine components, which can be implemented in various branches of mechanical engineering, including aerospace, automotive, and instrument manufacturing, to create ultra-wear-resistant contact elements.

Keywords: tribology; magnetic-resonance treatment; contact kinematic pairs; wear resistance; coefficient of friction; amorphization; microstructure; phase transformations; nanocrystalline structures.

С. В. КОВАЛЕВСЬКИЙ

МАГНІТНО-РЕЗОНАНСНА АМОРФІЗАЦІЯ МАТЕРІАЛІВ КОНТАКТНИХ КІНЕМАТИЧНИХ ПАР

У сучасному машинобудуванні вимоги до надійності та довговічності деталей постійно зростають, особливо для тих, що працюють в умовах інтенсивного тертя та високих контактних навантажень. Традиційні методи підвищення зносостійкості, такі як легування, нанесення покриттів або термічна обробка, часто виявляються недостатньо ефективними або мають обмеження щодо керованості й однорідності модифікації поверхні. У цій статті представлено інноваційний підхід до модифікації поверхневого шару матеріалів — магнітно-резонансну обробку, яка забезпечує формування унікальних мікроструктур, зокрема часткової аморфізації, безпосередньо в зоні контакту під час роботи. Метою дослідження є експериментальне обґрунтування застосування магнітно-резонансної обробки для формування аморфної фази у поверхневих шарах матеріалів контактних кінематичних пар з метою істотного підвищення їх зносостійкості. У роботі ґрунтовно розглянуто теоретичні засади та проаналізовано сучасні наукові дослідження у сфері модифікації поверхні й впливу сильних фізичних полів на структуру та властивості матеріалів. Особливу увагу приділено явищам самоорганізації та фазових перетворень, що відбуваються під час тертя під впливом магнітних полів. Експериментальні дослідження проведено на зразках сталі D2, які піддавалися магнітно-резонансній обробці на спеціалізованій установці. Випробування на тертя та зношування показали значне зниження коефіцієнта тертя (до 0,022–0,026) та інтенсивності зношування (у 3–4 рази), що свідчить про формування на поверхні надтвердих і надпластичних аморфних ділянок. Мікроструктурний аналіз за допомогою електронної мікроскопії та рентгенівської дифракції підтвердив утворення мартенситної фази й аморфних зон, а також зменшення розміру кристалітів до наномасштабу в зоні контакту. Обґрунтовано, що ці структурні зміни, індуковані резонансним впливом сильного магнітного поля, є ключовим чинником підвищення трибологічних характеристик. Отримані результати демонструють високу ефективність запропонованого методу магнітно-резонансної обробки. Встановлено, що під впливом сильних магнітних полів на поверхнях тертя формуються аморфні та нанокристалічні структури, які принципово змінюють механізми взаємодії поверхонь, мінімізуючи адгезійне та абразивне зношування. Це підтверджує гіпотезу щодо можливості керованої аморфізації матеріалів для підвищення їх експлуатаційної стійкості. Практичне значення дослідження полягає у розробленні нового, екологічно безпечного та енергоефективного методу збільшення ресурсу деталей машин, який може бути впроваджений у різних галузях машинобудування, зокрема в авіакосмічній, автомобільній та приладобудівній промисловості, для створення надзносостійких контактних елементів.

Ключові слова: трибологія; магнітно-резонансна обробка; контактні кінематичні пари; зносостійкість; коефіцієнт тертя; аморфізація; мікроструктура; фазові перетворення; нанокристалічні структури.

1. Introduction

In the global research arena, the issue of increasing the wear resistance of kinematic pairs occupies a special place due to the growing demands for the reliability and durability of mechanical engineering equipment. Accordingly, studies focus not only on traditional materials science approaches (alloying, creation of composite coatings, application of thin films) but also on innovative surface modification technologies capable of forming specialized microstructures in the contact zone directly during operation [1,2]. Most classical investigations are devoted to improving material compositions and introducing coatings (metallic, ceramic, diamond-like) to increase hardness and corrosion resistance [3]. However, under real operating conditions, such methods do not always provide the required level of protection, especially in the case of high contact pressures and abrupt temperature fluctuations. Thus, laser surface treatment enables the creation of a refined microstructure through localized heating and rapid cooling, sometimes resulting in the formation of martensitic or partially amorphous phases [4]. Yet, precise control of energy input and exposure time remains challenging, which limits the reproducibility and uniformity of the amorphous layer [5].

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Given the above, the relevance of this study lies in the search for new, effective, and controllable methods of modifying material surface layers to ensure enhanced wear resistance of machine components under extreme loading conditions.

The aim of the research is to improve the reliability of machine kinematic pairs by creating an amorphous layer on the contact surfaces using magnetic-resonance processing of materials (MRPM) in a two-component resonance vibration mode. To achieve this aim, the following interrelated objectives are proposed:

1. Development of a theoretical model of amorphization.
2. Optimization of two-component resonance regimes.
3. Validation of experimental results.

Thus, the overall aim combines theoretical elaboration of the amorphization mechanisms under two-component resonance, laboratory studies with high-precision measurement of microstructural parameters and tribological indices, and evaluation of the practical effect through statistical analysis of lifetime and reliability of kinematic pairs. As a result, an integrated picture is constructed of how the formation of an amorphous layer under the action of balanced normal and tangential vibrations alters friction mechanisms, wear intensity, and component durability.

The scientific hypothesis is that the synchronous action of two-component resonant loading—arising from the combination of normal and tangential vibrations in the presence of an external magnetic field—creates the most favorable conditions for the accumulation of defect energy, local heating, and activation of diffusion processes, leading to the formation of an amorphous layer on the contact surfaces of kinematic pairs.

2. Analysis of the results of previous research.

In many research laboratories in Germany, the USA, Japan, and other industrially developed countries, work has been intensified on the use of pulsed electromagnetic fields to form an amorphous phase in the material's contact zone [6]. Most such experiments focus on single-phase oscillatory modes, where either tangential (parallel to the surface) impulses predominate, or normal (perpendicular) impulses predominate [7]. The application of high-frequency tangential impulses in combination with a constant external magnetic field demonstrates the ability to form thin amorphous layers through the synergy of electromagnetic and thermal effects [8]. Existing publications consider the kinetics of the crystalline-to-amorphous transition under high-frequency electromagnetic excitation taking into account the thermal effect [9]. However, these models largely do not account for the combined action of oscillatory influences in different directions, leading to an inaccurate estimation of the amorphous layer thickness under real technological conditions. In a number of theoretical works, attention has been drawn to the correlation between the formation of an amorphous phase and an increase in service life, but there is no unified mathematical model that would provide an integrated picture of the dependence of the amorphous layer thickness on the amplitude, frequency, and ratio of the components of resonant oscillations [10].

In the international literature, experimental results are often reported showing that an amorphous layer reduces the coefficient of friction and extends the maintenance interval of parts by 2–3 times [11]. However, most studies focus on single-phase amorphization modes (laser or electromagnetic excitation), without considering the combined mechanical component [12]. Analysis of SEM and XRD images confirms the formation of an amorphous phase, but is rarely accompanied by extensive mathematical reliability calculations that take into account the dependence of wear intensity and failure functions on the actual increase in amorphous layer thickness [13].

The most significant gap lies in the limited number of systematic studies of two-component resonance, where normal and tangential oscillations are cohesively combined to maximally enhance local plastic deformation and high-frequency heating. Practically no published works combine precise calculation of tangential stresses depending on the synergy of different oscillation components, dynamic thermal effects, and prediction of the reliability function of a kinematic pair with regard to amorphization. Thus, although a significant body of knowledge on various surface amorphization methods (laser, electromagnetic, thermal) has been accumulated in world science, there is a lack of thorough studies that holistically cover two-component resonant oscillations and their impact on the mechanisms of amorphous layer formation, changes in friction coefficient, and prediction of reliability functions of kinematic pairs [14, 15]. This defines the need for comprehensive theoretical and experimental research integrating mathematical modeling, microstructure analysis, and real dynamic loading regimes.

In modern Ukrainian scientific and production structures, the problem of improving the wear resistance of surface technological elements is actively researched mostly within the framework of classical materials science and surface methods. Compared to leading global directions, domestic scientific schools have yet to develop a sufficiently systematic approach to integrating the latest surface modification methods under actual industrial conditions, and especially to the application of pulsed magneto-mechanical resonance treatment with two-component resonant oscillations [16].

3. Amorphization of surfaces in improving the reliability of machine-building parts.

The presence of an amorphous layer noticeably alters the surface properties [17]. First and foremost, the coefficient of friction decreases. The amorphous structure lacks clearly defined atomic slip planes, which prevents the formation of microcracks and brittle spalling [18]. This creates a “pseudo-surface” effect that functions as a damper under load.

The amorphous phase also exhibits high hardness. Due to the absence of a granular crystalline defect structure and “weak” points, the hardness of the layer increases by 20–30% compared to the base material. This enhances load-bearing capacity and extends the service life of components. Another advantage of the amorphous layer is its resistance to fatigue failure [19]. Unlike crystalline materials, where cracks predominantly propagate along slip planes, the amorphous layer has no such directional zones, so cracks occur less frequently and fatigue damage is deferred in time.

At the same time, the amorphous layer may be non-uniform in thickness. Depending on local conditions—deformation and thermal effects—it varies from several hundred nanometers to several micrometers.

The amorphous layer, or noncrystalline structure, arises in the contact zone thanks to the combination of high plastic deformation rates and localized temperature rises [20]. These conditions hinder the formation of an ordered crystalline lattice.

First, under the action of contact pressure and vibrations at the point of contact, the surface experiences localized shear. This destroys the crystalline structure, causing numerous dislocations and defects to form in the near-surface zone. If the deformation rate reaches 10^3 – 10^4 s⁻¹, the material does not have time to reorganize the lattice—the defects accumulate, and the zone transitions to a noncrystalline state [21]. Additionally, localized heating occurs in the contact zone due to thermoelectric effects and high stress concentrations. Temperatures in micro-regions may reach several thousand degrees Celsius, and the pulse duration is so short that partial breaking of crystalline bonds occurs. At the same time, the temperature is insufficient for the formation of large crystalline grains during subsequent cooling. After the heating cycle ends, extremely rapid cooling takes place - literally within fractions of a second. Under such conditions, crystals simply do not have time to grow, so the surface becomes amorphous, that is, devoid of a defined crystalline structure.

During deformation of the contact zones, where abrupt loads and local heating occur, numerous dislocations and other defects accumulate. There are so many that the material loses the ability to organize its crystalline lattice. If, in this process, the deformation energy and thermal effects exceed the bond energy in the metal, atoms begin to arrange in a chaotic order, which is the essence of the noncrystalline phase [22]. Equally important is the dependence of the amorphous layer thickness on various parameters. First, there is a certain plasticity threshold: if stresses in individual “hot spots” are below the yield limit, the amorphous layer simply does not form. Only after exceeding this threshold does the true noncrystalline transition begin. Second, the duration of exposure and the number of cycles matter: each pulse gradually increases the layer thickness. The more cycles, the deeper this layer becomes. However, it is important to remember that with excessive thickness, diffusion and recovery processes activate, which can partially return the material to a crystalline state. Third, the decisive factor is the balance between heating and cooling: if heating continues too long, it can lead to grain growth and formation of a crystalline or fine-grained structure. Therefore, it is extremely important that the heating pulse is short and quickly transitions to the cooling phase, preventing crystal nuclei from forming [23]. If the amorphous layer is sufficiently thick (several hundred nanometers), a characteristic gradient of properties forms within it. In the uppermost layer, maximum hardness and minimal internal stresses are achieved. Slightly below, a transition zone with partial crystallization appears, where micro-grains emerge. Even deeper, near the base material, regions with certain defects of the original crystalline lattice remain.

When a contact pair is treated by magnetic-resonance processing under two-component resonance conditions, an interesting feature is observed: at the initial stage, the wear curve is quite flat, indicating low wear intensity [24–27]. This continues until the amorphous layer thickness decreases to a certain critical value. If the layer thickness exceeds several hundred nanometers, it acts as a reliable barrier that prevents the emergence of sharp microscopic defects. Under such conditions, the surface effectively becomes self-lubricating, and the coefficient of friction decreases. But if the layer begins to thin, the intensity of defect formation sharply increases: the amorphous structure breaks down, exposing the subsurface region with micro-grained or even crystalline structure. This leads to a stepwise increase in wear. Regarding service life, an important indicator is the time to failure of 50% of the specimens (T_{50}). When the amorphous layer thickness exceeds 0.8–1.0 μm , T_{50} can increase by 2–3 times compared to the initial values. However, it should be noted that after the layer thickness falls below the critical threshold, T_{50} quickly approaches the original level—crystalline defects begin to dominate. From a reliability standpoint, one can use the reliability function $R(t)$, which shows the probability of failure-free operation of the contact pair over time. If the amorphous layer is thick, the failure rate is low, and $R(t)$ decreases very smoothly. But if the layer thins, $R(t)$ drops sharply, sometimes even abruptly—the amorphous region can no longer protect the surface from destruction. In practical applications, regular inspections of contact zones can be performed using, for example, scanning electron microscopy, atomic force microscopy, or hardness measurements. This allows precise determination of the residual thickness of the amorphous layer and prediction of approaching the critical service life. Thus, even before failures occur, replacement or maintenance can be scheduled, avoiding unexpected operational stoppages.

The analysis of the literature convincingly demonstrates that surface amorphization through various physico-chemical methods significantly enhances the mechanical and tribological resilience of components. However, the majority of studies focus on single-phase technologies (laser or electromagnetic amorphization). To date, the question of the interaction of different types of oscillations and the influence of the gradient structure on long-term reliability remains open. This opens up prospects for comprehensive research, especially under conditions of two-component resonant exposure.

4. Theoretical justification of MRPM.

MRPM is a technology of surface or local modification of metallic and non-metallic materials in which two interrelated physical factors act simultaneously [24–27]: mechanical nanovibrations of the surface layer of the specimen (amplitudes on the order of 10^{-9} – 10^{-8} m); high-frequency electromagnetic waves (frequency range $f_{EM} \sim 10^4$ – 10^6 Hz), consistent with the material’s own oscillatory characteristics ω_n ; all this occurs in a homogeneous constant magnetic field B_0 (a neodymium magnet) that sets the preliminary magnetostrictive or magnetoresistive state of the surface layer.

As a result of the combination of mechanical and electromagnetic resonant influence, a local rearrangement of the microstructure occurs (the formation of fine-grained, nanophase formations, an increase in the level of internal plastic deformations), which enhances the hardness, wear resistance, and, in general, the resource capacity of the material.

The surface layer of the material can be envisioned as a mass of m , suspended on effective stiffness k , with damping coefficient c . In the absence of external influence, its own oscillations are characterized by the natural frequency:

$$\omega_n = \sqrt{\frac{k}{m}}, \text{ rad/s} . \tag{1}$$

In the presence of a constant magnetic field B_0 There are two possible effects: magnetoresistive: a change in electrical conductivity or in the effective stiffness of the surface layer under the influence of B_0 , which leads to correction $k \rightarrow k_{ef}$ and $c \rightarrow c_{ef}$; magnetostrictive: emergence of internal stresses due to changes in the magnetic state (especially in ferromagnetic materials), which leads to additional initial stress $\sigma_0(B_0)$.

Equation of motion of a mechanical oscillator taking into account a constant field:

$$m\ddot{x}(t) + c_{ef}\dot{x}(t) + k_{ef}x(t) = F_{mech}(t) , \tag{2}$$

where $x(t)$ - is the vertical (normal) displacement of the surface layer; $F_{mech}(t)$ - is the external mechanical excitation force; $k_{ef} = k + \Delta k(B_0), c_{ef} = c + \Delta c(B_0)$.

If an alternating electric current is passed through the sample, then:

$$I(t) = I_0 \sin(\omega_{EM}t), \quad \omega_{EM} = 2\pi f_{EM} , \tag{3}$$

where f_{EM} lies in the range $\sim 10^4$ – 10^6 Гц.

This current creates an oscillating magnetic field:

$$B_{EM}(t) \propto \mu_0 \frac{I(t)}{r} . \tag{4}$$

A time-varying component of the field or of mechanical oscillations is superimposed on the static magnetic field acting on the entire volume of the sample, such that at every point in space the resulting influence is the vector sum of these two fields - $B_{EM}(t)$ and B_0 . Periodic combination of these fields generates a variable magnetoresistive or magneto-driven influence on local domains and structural defects. As a result, a mechanical force arises in the material layer:

$$F_L = I(t) \times B_0 , \tag{5}$$

which, when the electromagnetic frequency ω_{EM} is matched with the natural frequency ω_n causes an amplification of mechanical oscillations. $x(t)$.

Thus, the total excitation force in the equation of motion is equal to:

$$F_{mech}(t) = \alpha I_0 B_0 \sin(\omega_{EM}t) , \tag{6}$$

where α - coefficient that depends on the geometry of the sample and its electrical conductivity σ and magnetic permeability μ .

To achieve maximal nano-oscillations, it is necessary to tune ω_{EM} to the natural frequency ω_n , that is:

$$\omega_{EM} \approx \omega_n \Rightarrow 2\pi f_{EM} \approx \sqrt{\frac{k_{ef}}{m}} . \tag{7}$$

In such a case, the amplitude of mechanical oscillations x_{max} reaches its maximum:

$$x_{max} \approx \frac{\alpha I_0 B_0}{m[2\zeta\omega_n]}, \quad \zeta = \frac{c_{ef}}{2k_{ef}m}. \quad (8)$$

Since $\zeta \ll 1$ (small damping in the nano-range), even a relatively small $I_0 B_0$ can give rise to $x_{max} \sim 10^{-9} - 10^{-8}$ nanometer oscillations.

As a result of the combination of two (resonant) modes, the following occur:

- mechanical resonance, in which:

$$m\ddot{x}(t) + c_{ef}\dot{x}(t) + k_{ef}x(t) = \alpha I_0 B_0 \sin(\omega_{EM}t), \quad \omega_{EM} \approx \omega_n \quad (9)$$

- magneto-resistive influence.

The parameters k_{ef} and c_{ef} depend on B_0 . For example, for certain ferromagnetic steels, one can write:

$$\Delta k(B_0) = \kappa_k B_0^2, \quad \Delta c(B_0) = \kappa_c B_0^2, \quad (10)$$

where κ_k, κ_c - material-dependent coefficients.

As a result of the resonance regime, increases in the intensity of plastic deformation in the subsurface layers are observed due to nanovibrations that stimulate the dissolution of defects and grains; an increase in the rate of diffusion processes (through oscillations), which activates phase transformations (formation of oxide nanolayers, impurity enrichment); the development of magneto-resistive and magnetostrictive effects simultaneously with mechanical loading, which contributes to an increase in the kinetic energy of defects and grains.

During MRPM, energy of plastic deformation accumulates in the surface layer of the material, which is caused by intensive nano-oscillations. The criterion for the onset of amorphization is the excess of deformation energy over the binding energy in the crystalline lattice. Let us denote E_d - the energy required to destroy the crystalline structure per unit volume (the activation energy of amorphization); and W_p - the energy of plastic deformation accumulated per unit volume of the surface layer.

The amorphization condition can be written in the form:

$$W_p \geq E_d. \quad (11)$$

Let the mechanical nano-oscillatory Lorentz force $F_L(t)$ with resonance frequency ω_n lead to a periodic oscillatory loading. The average power expended on plastic deformation in volume V per oscillation is estimated as:

$$P_p = \int_0^T \sigma(t) \dot{\epsilon}(t) dt, \quad (12)$$

where $\sigma(t)$ - cyclic stress, $\dot{\epsilon}(t)$ - the rate of plastic deformation, $T = 2\pi/\omega_n$.

Average density of accumulated energy after N cycles:

$$W_p = \frac{NTP_p}{V} \approx \frac{NT(\sigma\dot{\epsilon})}{V}. \quad (13)$$

Under resonance conditions, mechanical oscillations reach the maximum amplitude A_{max} , therefore the stress σ and the strain rate $\dot{\epsilon}$ increase. Then, after N_{cr} cycles, the accumulated energy may exceed E_d :

$$N_{kp} \approx \frac{E_d V}{(\sigma\dot{\epsilon})T}. \quad (14)$$

When $W_p = E_d$, the irreversible (amorphous) transition of the surface layer begins. If an alternating current of frequency ω_{EM} , tuned to the mechanical resonance ω_n , flows through the specimen, a radially distributed demagnetizing effect is created. As a result of the periodic magneto-resistive change of material parameters (Young's modulus, damping coefficient), additional generation of internal stresses (magnetostriction) occurs. The energy of this influence W_{EM} is also accumulated in the subsurface layer due to the anisotropy of the magnetic domains:

$$W_{EM} \approx \int_0^T M(t) dH(t) \approx \mu_0 \chi H_0 h V, \quad (15)$$

where $M(t)$ - magnetization, $H(t) = H_0 \sin(\omega_{EM}t)$ - alternating field, χ - magnetic susceptibility, h - amplitude of magnetoresistive change, μ_0 - magnetic constant.

Under resonant conditions $\omega_{EM} \approx \omega_n$ local defect sites receive an additional energy impulse, which promotes the activation of diffusion processes and local heating:

$$\Delta T(z) \sim \frac{W_{EM}}{\rho c_p V}, \quad (16)$$

where ρ - material density, c_p - specific heat capacity.

Local increase of temperature $\Delta T(z)$ accelerates diffusion and promotes phase transformation. The total accumulated energy in the subsurface layer:

$$W_{tot} = W_p + W_{Em}. \quad (17)$$

If $W_{tot} \geq E_d$, the conditions for amorphization are met faster than under purely mechanical action.

As a result of intensive nanovibrations in the layer with a thickness $d_{ш}$ (on the order of $\sim 0,1 \dots 1$) cyclic plastic deformations with shear amplitudes $u_{amp} \approx 10^{-9} \dots 10^{-8}$, м. The plastic accumulation of dislocations (ρ_{disl}) causes rapid fragmentation of the crystalline structure into fine grains (розмір D_{gr}). According to the modified Hall-Petch law:

$$\sigma_y = \sigma_0 + k D_{gr}^{-1/2}, \quad (18)$$

where σ_y - yield strength, σ_0 - the supporting stress of large grains, k - a material-dependent coefficient.

Reduction of D_{gr} to the nano-range leads to a significant increase in σ_y , but at the same time, the internal accumulated stresses and the stored energy of defects also increase W_{plast} :

$$W_{plast} \propto \int_0^{\rho_{max}} \tau d\rho, \quad (19)$$

where τ - shear stress.

When the dislocation density reaches a critical level ρ_{cr} , the atomic planes can no longer restructure into an ordered system, as the defect energy exceeds the migration energy. This leads to the formation of an amorphous (non-crystalline) state.

Parallel to the accumulation of dislocations under the influence of nano-vibrations, diffusion mechanisms are activated: atoms in the subsurface layer are mobilized due to oscillatory displacement and local heating. The specific diffusion rate D at the temperature $T + \Delta T$:

$$D(T + \Delta T) = D_0 \exp\left(-\frac{Q}{R(T + \Delta T)}\right), \quad (20)$$

where D_0 - pre-exponential factor, Q - activation energy of diffusion, R - gas constant.

Even a slight increase in ΔT (tens of degrees) sharply increases D , which accelerates atom movement and filling of inter-dislocation gaps. Under conditions of high defect density, this creates an unstable configuration where the local structure tends toward an energy minimum. However, due to the excessive concentration of defects and the energy of jumps, amorphous zones form, which lack long-term order.

Для утворення аморфного шару необхідно досягнути певного критичного зсуву γ_{cr} у поверхневому шарі, при якому відбувається суцільна дезорієнтація частинок. Згідно з теорією деформаційної аморфізації:

$$\gamma_{cr} \approx \frac{2\pi a}{\sqrt{3} D_{gr}}, \quad (21)$$

where a - interatomic distance.

For $D_{gr} \sim 5 \dots 20$, nm, we obtain $\gamma_{cr} \approx (0,1 \dots 0,3)$. In mechanical nanovibrations, the displacement amplitude u_{amp} and frequency ω_n determine the maximum shear rate $\dot{\gamma}_{max} = \omega_n u_{amp} / d_{ш}$. If $\dot{\gamma}_{max} \cdot \tau_{cycle} \geq \gamma_{cr}$, where $\tau_{cycle} = 2\pi / \omega_n$, then during one cycle of nanovibrations the critical shear value occurs. At resonance $\omega_n \approx \omega_{EM}$ the damping β is minimal, so the amplitude u_{amp} reaches its maximum value, which ensures the condition $\gamma \geq \gamma_{cr}$.

To transition to an amorphous state, it is sufficient to achieve:

1. A high density of accumulated defects ($\rho_{disl} \geq \rho_{cr}$),
2. A local increase in temperature $\Delta T \geq T_d$,
3. A critical sheary $\geq \gamma_{cr}$,

4. Instability of the crystal lattice: $W_{tot} = E_d$.

When these conditions are simultaneously met, an amorphous layer is formed at a depth d_{amor} the thickness of which depends on the depth distribution of nanovibration intensity and the heating field profile:

$$d_{amor} \approx \sqrt{2D(T + \Delta T)t_{exp}}, \quad (22)$$

where t_{exp} - total exposure time (sum of cycles), D - diffusion coefficient.

Under typical MRPM mode with $\omega_n \sim 105, rad/s$, $u_{amp} \sim 10^{-9}$, $H_0 \sim 0,5$, T the thickness d_{amor} lies in the range $(0,2...1), \mu m$.

Thus, the final proof of the formation of the amorphous layer is determined by the following: accumulation of plastic deformation energy: intense nanovibrations at resonance lead to rapid accumulation of defect energy W_p , which exceeds E_d after N_{cr} cycles; electromagnetic resonance influence: magnetoresistive and magnetostrictive effects generate additional stress and local heating ΔT , which increases the diffusion rate and lowers the defect formation energy; quantized deformation cycles and shear: under the condition $\omega_{EM} \approx \omega_n$ the amplitude of nanovibrations reaches u_{amp} , which ensures shear $\gamma \geq \gamma_{cr}$ in a single cycle, destroys the organized crystal lattice and initiates a local transition into the amorphous phase; due to diffusion processes at a depth d_{amor} a stable amorphous layer is formed.

Thus, the fulfillment of all the mentioned conditions indicates that, under the influence of MRPM, an amorphous zone arises and develops in the surface layer. This proof is based on energetic considerations (accumulation of defect energy), crystallographic instability conditions (critical shear and dislocation density), and the activation of thermodynamic and diffusion processes.

5. Results of experimental studies and their discussion.

A detailed description of the results of experimental studies devoted to the effect of magnetic resonance processing in a dual-component resonance mode (MRPM) on the characteristics of the contact surfaces of a "shaft-bushing" pair is presented. Special attention is paid to microstructural changes, morphological features, changes in hardness, and the tribological properties of the surface layer after MRPM.

After performing a series of MRPM cycles, significant changes were revealed in the surface layer of the contact element, especially in the central zone, which can be considered a "hot spot." In this zone, where mechanical and electromagnetic influences are most intense, the average thickness of the amorphous layer was about one micrometer. However, this value proved to be non-uniform, ranging from 0.8 to 1.2 micrometers depending on the localization along the contact line. A more detailed study of the thickness profiles obtained using scanning electron microscopy (SEM) showed that the maximum thickness values are concentrated in the center of the "hot spot." This area coincides with the zones of maximum normal and tangential stress components of the oscillations. Moving several hundred micrometers away from the center, the thickness of the amorphous layer gradually decreases, forming a gradient that transitions into a zone less protected from deformation impact. A significant heterogeneity of the layer thickness was revealed in the cross-section of the surface. In particular, two local maxima of thickness were recorded along the diagonals of the "hot zone." This phenomenon is explained by the phase-heterogeneous superposition effect of mechanical and electromagnetic pulses, which leads to the appearance of two peaks of energy concentration where a so-called "cluster resonance" is formed. This effect confirms the uniqueness of the dual-component MRPM mode compared to classical single-phase approaches.

The morphological features of the surface after MRPM, determined using atomic force microscopy (AFM), show an almost smooth texture. The average profile protrusion (Ra) is only about 0.03–0.05 micrometers, indicating a low level of microroughness. At the 1×1 micrometer detail level, the surface consists of small fragments lacking a crystalline ordered structure, indicating the amorphous nature of the layer. In areas distant from the center of the "hot zone," isolated shallow pits up to 0.1 micrometers deep were observed using AFM scanning. Their appearance is most likely associated with local temperature increases at the moment of impulse loading when the zone could not cool quickly enough. These pits were mainly located outside the main contour of the resonant influence, where normal and tangential oscillations interacted less intensively. A detailed analysis of the topographic descriptors in the central "hot spot" showed that the relative height dispersion was only about 10–12%. This indicates a sufficiently homogeneous structure of the amorphous layer. At the same time, in the transition zone, approximately 0.5 millimeters from the center, the height deviation increased to 25%. This increase is explained by a decrease in the amplitude of tangential oscillations and a reduction in the intensity of mechanical resonant influence.

Before MRPM, the surface hardness in the initial state (the running part of the bushing before chemical-mechanical processing) was approximately 58–60 HRC (Rockwell scale). The microstructure in this state consisted of fine-grained martensite with minor residual stresses formed after prior quenching and tempering. After performing MRPM, the hardness in the central zone of the amorphous layer increased significantly to 800–900 HV on the Vickers scale. This corresponds to approximately 62–64 HRC, demonstrating an increase in hardness by 5–7 HRC compared to the initial state. This increase in hardness indicates that the absence of a crystalline lattice and the chaotic arrangement

of atoms in the amorphous structure provide increased resistance of the material to point damage. In the zone where the thickness of the amorphous layer decreased to 0.5–0.7 micrometers, the hardness gradually decreased to 700–750 HV. This indicates a transition to an intermediate zone where the amorphous structure partially crystallizes. Further, in the layer with a thickness of 0.2–0.3 micrometers, the hardness decreased to 600–650 HV, corresponding to the main crystalline sublayer.

Detailed analysis of several samples revealed a clear correlation between the thickness of the amorphous layer and hardness: maximum hardness values coincided with the greatest layer thickness. A decrease in thickness was accompanied by a proportional reduction in hardness down to the level of the crystalline material, confirming the key role of the amorphous structure in increasing hardness. Particularly noteworthy is that in the thickness range of 0.6 to 0.8 micrometers, hardness decreased more rapidly than in the central range of 1.0–1.2 micrometers. This is explained by the fact that at a lower thickness of the amorphous layer, the load was more quickly transmitted to the crystalline sublayer, since the number of amorphous cells capable of effectively dissipating stress became insufficient. Regarding the measurement accuracy, the error in the mean hardness values in the central zone was about $\pm 2\text{--}3\%$, while in the transitional zone it increased to $\pm 5\%$. This was due to both the non-uniform formation of the amorphous layer and variations in the surface roughness of the sections after polishing.

Analyzing the change in the friction coefficient μ , it was found that for the untreated surface, the mean value of μ in the “shaft–bushing” pair was approximately 0.12 under mineral oil lubrication at a temperature of about 25 °C and atmospheric pressure. Such a friction level is typical for D2 steel friction pairs. After the formation of the amorphous layer as a result of MRPM, the mean value of μ for the first 10,000 revolutions decreased to 0.10–0.11. This indicates a reduction in friction by 8–10% due to a smoother topography and the presence of a hard amorphous surface, which prevents the mechanical “seizure” of microasperities. During operation up to 50,000 revolutions, the friction coefficient remained within 0.10–0.12, demonstrating stable performance of the amorphous layer. After 60,000 revolutions, when the thickness of the amorphous layer decreased to approximately 0.6 micrometers, the friction coefficient began to gradually increase, reaching values of 0.13–0.14 by 100,000 revolutions. In the final interval (150,000–200,000 revolutions), the μ value reached 0.16–0.17, approaching the initial values of the untreated surface. The standard deviation of the friction coefficient during the stable sliding period (up to 50,000 revolutions) was about 5%. In the accelerated wear zone (over 100,000 revolutions), this indicator increased to 12–15%, indicating non-uniform destruction of the amorphous layer in different samples.

Regarding the wear rate K_w , in the first interval (up to 20,000 revolutions), its value remained minimal—approximately 0.05 mm per 10,000 revolutions. This corresponds to a state where the amorphous layer still provided protection against deep microdamage. During the moderate wear period (20,000–60,000 revolutions), when the layer thickness decreased to 0.8–0.6 micrometers, the wear rate increased to 0.1–0.12 mm per 10,000 revolutions. This was due to the depletion of the layer under the influence of mechanical and thermal loads and the exposure of the crystalline material sublayer. When the thickness of the amorphous layer dropped below 0.5 micrometers, the wear rate reached 0.2–0.25 mm per 10,000 revolutions. This indicated the onset of dominant crystalline wear. At this point, microcracks and fragmentation of the surface layer were observed, leading to a rapid deterioration of tribological properties. For comparison, in the control samples without MRPM, the wear rate already at the beginning of operation exceeded 0.2 mm per 10,000 revolutions, and by 100,000 revolutions increased to 0.5 mm per 10,000 revolutions. This clearly demonstrates that the amorphous layer after MRPM provided significantly better wear protection for a certain period than the initial crystalline coating.

6. Discussion of the results.

After the formation of the amorphous layer, its thickness proves to be closely associated with the reduction of the coefficient of friction between the contacting surfaces. In particular, in the so-called “hot spots”—areas where the layer thickness reached approximately one micrometer—the surface was found to be virtually perfectly smooth, without pronounced crystalline grains or sharp defects. Such a surface, free of microasperities, significantly reduced the interaction between surfaces, which, in turn, contributed to a “self-lubricating” effect. On such an amorphous surface, there are no distinct sliding directions, since the atomic structure does not exhibit classical crystalline order. When the thickness of the amorphous layer decreased to 0.6–0.8 micrometers, the coefficient of friction began to gradually increase. This is due to the formation of a transition zone beneath the thin layer, where signs of partial crystallization already appeared. In this zone, the amorphous cells no longer performed the function of an effective barrier, and local micro-roughnesses began to interact with each other, leading to an increase in friction. In the thinnest areas, with a thickness of 0.2–0.4 micrometers, the amorphous layer was almost completely destroyed, and the surface acquired properties similar to the original crystalline structure of D2 steel. Thus, the experimental results demonstrate that the thickness of the amorphous layer directly affects the level of friction: from a minimum value at a thickness of about 1 μm to values approaching the initial ones in the case of the thinnest layers. These observations confirm the known notions about the mechanism of friction reduction due to the formation of the amorphous phase, in which there are no flat sliding directions and there is a reduced tendency for debris formation. However, our data significantly refine this concept, showing that it is not just the presence of the amorphous structure but its sufficient thickness that determines the effectiveness of friction reduction. Unlike many literature studies, which record predominantly local formation of thin layers, in our case, it was possible to clearly distinguish three zones: maximum thickness ($\sim 1 \mu\text{m}$), gradient zone

(~0.6–0.8 μm), and thin zone (<0.5 μm). Each of these zones affects the coefficient of friction differently, allowing for a more precise determination of when the transition from the “amorphous” to the “crystalline” friction mechanism occurs.

Experimental studies using different combinations of mechanical (normal) and electromagnetic (tangential) impulses made it possible to identify the optimal parameters at which the maximum thickness of the amorphous layer is achieved. The best results were observed when the power ratio between the tangential and normal components was approximately 0,7 : 1,0, and the difference in vibration frequencies was 5–7 kHz. Under these conditions, in the “hot spots,” there was a twofold increase in the rate of defect accumulation in the crystalline structure. Local heating in these areas reached an optimal level sufficient to prevent the grains from restoring an ordered lattice during cooling. This created conditions for the fastest possible formation of the amorphous phase.

A nonlinearity effect in the resonant interaction was also observed. When the amplitude of one of the components increased in the nonlinear mode, the resonance point shifted, resulting in the formation of two local zones of peak energy accumulation instead of a single classical peak. This behavior led to the emergence of two “hot spots,” accompanied by local variations in the thickness of the amorphous layer, up to its unpredictable increase in certain areas. Sometimes such nonlinear interaction led to the formation of local defects (mini-pits) when the energy impact exceeded the optimal threshold. Therefore, it is important to consider that an excessive increase in amplitude does not always lead to an increase in the thickness of the amorphous layer: at certain values, mechanisms of recrystallization and microstep formation begin to operate, which affect the uniformity of the layer.

The results of experimental studies of reliability functions showed that amorphization due to MRPM significantly affects the durability of components. In particular, the reliability function curve clearly demonstrated a threefold shift of the “50% failure point” compared to the untreated crystalline surface. This means that in practical conditions, when half of the “shaft–bushing” assemblies already require repair, the MRPM-treated elements still retain about 80% of their operational capability. Thus, this allows for significantly less frequent maintenance, reducing the downtime of equipment caused by the replacement of worn parts. An economic analysis confirmed that investments in the MRPM procedure pay off after the first usage cycle due to the increased maintenance interval. Despite the rather high cost of equipment and significant energy consumption, the profitability of implementing MRPM in medium- and large-scale production is beyond doubt. Each “shaft–bushing” in such production can obtain an amorphous layer with minimal thickness deviations, ensuring stable operating life of 600–650 hours without the need for additional repair operations.

However, despite the positive effect, attention should be paid to some limitations that affect the accuracy of experimental data and their interpretation. Firstly, the use of scanning electron microscopy (SEM) and atomic force microscopy (AFM) produced an error of up to $\pm 0.05 \mu\text{m}$, which, with a total thickness of up to 0,2 μm , could lead to an error of up to 8%. Secondly, even slight deviations in the phase of normal and tangential vibrations caused local variations in the thickness of the layer, which was reflected in the heterogeneity of tribological characteristics. Thirdly, in laboratory conditions, the cooling rate after the impulse was stable, but in industrial environments, where it is difficult to ensure precise temperature control, uneven cooling is possible, which can lead to partial recrystallization of the amorphous layer.

When forming amorphous layers using single-phase methods (laser or electromagnetic treatment), the layer thickness usually does not exceed 0.7–0.8 μm . In these cases, the coefficient of friction can be reduced by only 10–15%. However, this is not enough to significantly increase the service life of components, since the maintenance interval in such studies increased by only 50–80% compared to the crystalline state. In contrast, in our studies, the application of the two-component resonant approach made it possible to achieve a layer thickness of up to 0,3 μm , which provided an almost threefold increase in service life.

The difference in our approach lies in the use of synchronized normal and tangential impulses. Unlike other researchers, who usually applied either an alternating field to the crystalline surface or exclusively mechanical vibrations, we combined these modes to create a deeper and more uniform amorphous layer. Additionally, our approach includes a multi-level analysis—from SEM/AFM studies to long-term tribological tests and “shaft–bushing” stand tests. This allowed not only to record the fact of friction reduction but also to establish a clear correlation between layer thickness, its microstructural characteristics, mechanical hardness, wear resistance, and reliability functions. Most literature sources usually investigate only one or two of these aspects, which limits the understanding of the method's effectiveness. Furthermore, our work provides recommendations for industrial integration, which include phase tuning parameters for optimal amorphization, economic calculations, and critical layer thickness limits for maintenance planning. Unlike many studies that remain at the level of laboratory recommendations, our approach is aimed at practical application in real production conditions.

7. Recommendations for further research.

It is necessary to focus on the development of an automated system for controlling and adjusting the phase shift during MRPM. The use of high-speed position sensors, electronic phase detectors, and “fast” correction will reduce the human factor and thus decrease the risk of forming irregularities and local defects.

It is recommended to conduct studies in which MRPM-treated parts will be operated under real load conditions (temperature fluctuations, presence of abrasive particles, corrosive-aggressive environment) for extended periods. This will allow an assessment of how well the amorphous layer retains its properties under harsh conditions and whether

adjustments to processing parameters are required. Experiments should also be extended to other tool steels (e.g., M2, S7), alloyed powder composites, and new composite materials (especially nanostructured mixtures). Since amorphization mechanisms depend on thermal conductivity and plasticity, the ratio of amplitudes and frequencies should be optimized for different alloys to establish universal algorithms for these classes of materials.

It is advisable to carry out more detailed calculations of the total cost of ownership (TCO), taking into account overhead costs (prolonged equipment downtime, energy costs, maintenance of the MRPM system), as well as expenses related to disposal or repair of components. This will help develop sound business cases for different industries and scales of production.

Based on the obtained data, it is advisable to develop and standardize a step-by-step technological process regulation:

- 1) surface preparation (polishing, cleaning);
- 2) selection of optimal amplitudes and vibration frequencies for the specific material;
- 3) adjustment of the phase shift between components;
- 4) control of temperature and cooling rate during each impulse;
- 5) measurement of layer thickness and hardness after each series of cycles;
- 6) criteria for terminating impulses and completing processing.

Such a regulation will minimize errors, ensure repeatability, and reduce the likelihood of local defects.

It is recommended to implement monitoring of the residual thickness of the amorphous layer in production using a portable SEM scanner or ultrasonic probe. If the thickness approaches ≈ 0.6 micrometers, it is necessary to plan for repeated MRPM or replacement of the component, as this is where a rapid increase in the coefficient of friction and wear intensity occurs. These thresholds can also serve as the basis for maintenance scheduling, helping to prevent catastrophic failures. In repair shops where "shaft-bushing" assemblies are regularly restored, separate MRPM modules equipped with mobile coils and compact piezo elements should be provided. This will enable on-site amorphization, reducing transportation costs and possible equipment downtime.

Before launching high-speed MRPM production, it is necessary to conduct training programs for engineers and operators, explaining the specifics of phase setup, data acquisition from thermocouples and strain gauges, and interpretation of SEM/AFM results. It is also advisable to create a knowledge base ("expert database") where best practices and technical nuances for different materials and processing modes can be recorded.

8. Conclusions.

The distinction of this study from previous ones lies in the comprehensive consideration of the surface amorphization process under the simultaneous action of two components of resonant vibrations: normal (perpendicular to the contact surface) and tangential (parallel to the surface). Most existing studies focused either on the influence of high-frequency tangential impulses in combination with static loads or exclusively on laser/electromagnetic single-phase processes without considering the mechanical component. In the proposed approach, a method for synchronous control of a hydraulic drive (for normal vibrations) and an electromagnetic drive (for tangential impulses) has been developed and implemented. This interaction makes it possible to achieve the effect of high-frequency local heating while simultaneously actively forming plastic deformation, which contributes to a much deeper and more homogeneous formation of the amorphous layer.

Unlike most works that propose empirical relationships of the amorphous layer thickness from individual parameters (frequency of one type of vibration or the value of the external magnetic field), a conceptual scheme is formulated here that explains how exactly normal and tangential impulses interact in resonance. An analysis of the superposition of these components was carried out, optimal power ratios P_t/P_n and frequency divergence $\Delta\omega$ were identified to achieve the maximum level of local mixing of the material lattice and the formation of an amorphous layer up to ~ 1.2 μm thick. Experimental studies demonstrated that the superposition of synchronized normal and tangential vibrations significantly enhances the formation of an amorphous layer. The uniqueness of this method lies in the fact that, at the same energy expenditure, the thickness of the amorphous layer in the two-component resonance exceeds the indicators of single-phase approaches by almost one and a half to two times. In the central "hot spots," the layer thickness reached about one micron and more, which significantly exceeded the usual values for single-phase electromagnetic or laser treatment (≈ 0.7 – 0.8 microns). This result confirms that it is precisely the coordination of the phases and amplitudes of the two vibration components that creates the most favorable conditions for the accumulation of crystal lattice defects and the rapid transition of the material to the amorphous state.

The formed amorphous layer was characterized by increased hardness (equivalent to approximately 62–64 HRC) compared to the original crystalline material (58–60 HRC). This hardness level was observed in the central areas where the layer thickness was the greatest. The gradual decrease in hardness with a decrease in the thickness of the amorphous layer confirmed the gradient structure: in the zone where the thickness exceeded 0.8 microns, the hardness remained at a high level, and approaching the limit of ≈ 0.4 – 0.5 microns, the hardness already approached the initial value. This indicates that the amorphous layer acts as a "protective barrier" to a certain depth, which allows the contact surface to exhibit increased resistance to external loads. The formation of the amorphous layer caused a decrease in the friction coefficient by approximately 8–10% during the first tens of thousands of operating cycles. This was explained by the smoother topography, the absence of crystalline grains, and the microasperity interaction. The

wear intensity during the formation period and the initial "life" of the amorphous layer was minimal (≈ 0.05 mm per 10,000 revolutions). Only after the layer thickness decreased below ≈ 0.6 microns did the wear intensity begin to increase sharply, transitioning from a "light" to an "accelerated" stage. In the untreated group, the wear intensity from the first cycles was ≈ 0.2 mm per 10,000 revolutions and continued to increase, which confirms the protective function of the amorphous layer.

Bench tests of the "shaft–bushing" assembly showed that the MRPM-treated samples were able to operate without serious signs of wear for approximately 480–600 hours (or 80,000–110,000 revolutions) before the appearance of the first microcracks and critical wear (0.1 mm). In contrast, the control samples without MRPM failed (appearance of microcracks) after 150–220 hours. Thus, the mean time between repairs in the MRPM-treated samples increased approximately threefold. The constructed reliability functions show that at the point where 50% of the samples no longer meet the criteria for trouble-free operation, the MRPM-treated samples still remain at over 80% serviceability.

A comparative analysis of the costs of traditional replacement of the "shaft–bushing" assembly and the costs of performing MRPM demonstrates significant savings. If the traditional replacement of one assembly for full resource recovery requires conditionally 1000 units of expenditure and provides approximately 200–220 hours of operation, then performing MRPM costs about 100 units and makes it possible to extend the resource to 600–620 hours. Thus, the conditional cost of one hour of trouble-free operation with MRPM is approximately 20–25 times lower than with the traditional approach. These figures indicate the high cost-effectiveness of the method, especially in large-scale serial production or costly equipment downtime. Although the study was performed on D2 steel, the obtained results indicate that the approach is generally universal and suitable for various tool and structural steels with similar mechanical and thermal properties. The key element is the adjustment of parameters (amplitudes and vibration frequencies) according to the thermal conductivity, plasticity, and heat resistance of the specific alloy. This creates the potential for scaling the technology to other materials and applications — from the defense industry to energy and heavy engineering.

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About the Authors / Відомості про авторів

Kovalevskyy Sergiy (Ковалевський Сергій Вадимович) – Doctor of Engineering, professor, Head of the Department of innovative technologies and Management Donbas State Engineering Academy (Kramatorsk-Ternopil, Ukraine) E-mail: kovalevskii@i.ua. ORCID: <https://orcid.org/0000-0002-4708-4091>