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IMPROVING THE WEAR RESISTANCE OF PROFILED PARTS OF BINDING EQUIPMENT BY FORMING A MICRORELIEF USING THE ULTRASONIC BURNISHING METHOD

The object of this research is the process of improving the wear resistance of profiled components of bookbinding equipment by forming a strengthening microrelief using ultrasonic rolling. The study is analytical and theoretical in nature, based on mathematical modeling of contact loading, microplastic deformation, and surface roughness parameters induced by ultrasonic rolling.

Keywords: wear resistance; mathematical modeling; microrelief; ultrasonic rolling; indenter; residual stress; profiled steel components; modified wear model.

Introduction

Improving the wear resistance of components operating under contact friction conditions is a key direction in ensuring the reliability and service life of printing and binding equipment. In particular, profile elements such as guide strips, pressing parts, and folding profiles play a crucial role in the performance of bookbinding machines. During operation, these components are subjected to significant loads due to cyclic contact interactions, pressure, and vibration. Over time, this leads to surface wear, resulting in a loss of positioning accuracy and a decrease in the quality of bound products.

Conventional methods for enhancing surface durability — such as thermal treatment or the application of hard coatings — are often unsuitable for components with complex profiles or thin-walled structures. These techniques may cause deformations, uneven hardening, or the formation of microcracks due to excessive local hardness without considering the actual stress distribution in the contact zone.

This has prompted growing interest in non-thermal surface treatment technologies that allow controlled modification of surface microgeometry, improve tribological performance, and preserve the geometric integrity of the parts. Among these, ultrasonic burnishing has shown significant potential, as it combines localized plastic deformation with high-frequency vibration of the tool. This treatment enables the formation of microrelief structures with increased hardness, a densified susurface layer, and reduced surface friction.

Given the advantages of ultrasonic burnishing, it becomes relevant to explore its application to the specific conditions and material profiles used in bookbinding machinery. In particular, it is necessary to investigate its effectiveness in enhancing the performance and durability of steel profile components operating under cyclic loading conditions.

Despite the demonstrated advantages of ultrasonic burnishing, its use in the field of printing and binding equipment has not yet been sufficiently studied. Adapting this method to the processing of profiled and thin-walled parts presents certain challenges, particularly in ensuring both effective surface strengthening and preservation of form accuracy. It is known that the microgeometry of such components has a direct impact on the stability of block positioning, the precision of fold formation, and the uniformity of material feeding.

Degradation of surface microgeometry due to wear increases friction, causes misalignment, and accumulates errors during assembly, ultimately reducing the quality of printed products. This leads to increased maintenance frequency and shortens equipment service life.

The issue is further complicated by the fact that most structural elements have complex shapes, making it difficult for conventional treatment methods to deliver uniform hardening effects across the surface. Additionally, inadequate control over the formation of the subsurface layer without regard to contact stresses may result in uneven wear and premature failure.

To date, the following important aspects remain insufficiently explored:

— Optimal process parameters for ultrasonic burnishing of profiled steel parts in bookbinding mechanisms;

— The influence of the generated microrelief on tribological properties such as wear, friction coefficient, and contact stability;

— The correlation between surface geometry, structural changes in the subsurface layer, and the fatigue life of the part.

Accordingly, there is a need for a comprehensive study of ultrasonic burnishing as a surface-strengthening technology capable of forming an optimized microrelief that enhances wear resistance and ensures reliable long-term operation of profile components in bookbinding equipment.

An analysis of current research in the field of ultrasonic surface strengthening demonstrates the effectiveness of this method for improving the performance characteristics of machine components. In particular, study [1] investigates the effect of ultrasonic burnishing on the surface integrity of flat specimens. Positive results were obtained regarding surface roughness reduction and hardness increase. However, the study does not address the processing of profiled surfaces, which are typical for components of bookbinding equipment. Furthermore, it lacks an analysis of wear resistance under contact interaction with soft materials such as paper or cardboard.

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In [2], ball ultrasonic burnishing with vibrational support was studied for cylindrical stainless-steel specimens. Although improvements in tribological properties were observed, the study does not consider friction conditions under low sliding speed and localized pressure, which are characteristic of folding mechanisms. Additionally, no data are provided on the ability to generate microrelief with a controlled orientation and profile.

The authors of [3] investigated surface effects resulting from vertical ultrasonic burnishing of aluminum blanks. While the study focuses on surface roughness and surface quality, it does not analyze wear resistance or wear mechanisms. The formation of functional microrelief as a target outcome of processing is also not addressed.

Study [4] analyzed the mechanism of microrelief formation under two-dimensional ultrasonic burnishing. Although the results confirm the generation of a regular structure with increased hardness, the research is limited to aluminum alloys and does not consider the behavior of steel, which is the primary material used in profiled components of printing and binding equipment. Moreover, the compatibility of the formed relief with the technological requirements of the bookbinding process remains unexplored.

Publication [5] considers the combination of laser cladding with ultrasonic burnishing for applications involving high-temperature friction. However, the study is focused on large-sized steel components and does not address thin-walled or narrow-profile elements subject to elastic deformation, which are typical in bookbinding systems. No data are presented regarding the effectiveness of the generated microrelief under repeated short-term loading conditions.

Study [6] reports a positive influence of ultrasonic burnishing on the characteristics of parts produced using the L-DED method. Nevertheless, the work does not include an analysis of surface structures with curved or complex profiles, which are typical of guide or folding strips. In addition, it does not investigate the stability of the formed relief under cyclic deformation.

Particular attention should be paid to the works of Ukrainian researchers [7, 8], which substantiate the feasibility of applying plastic deformation methods to improve wear resistance. Although these studies do not focus specifically on ultrasonic burnishing, their conclusions confirm the effectiveness of surface strengthening approaches for components with complex geometry.

Study [9] focuses on the strengthening of thin-walled titanium elements with holes. The research is conducted in the context of fatigue strength of aerospace components, without adaptation to the frictional conditions typical of paper-processing machinery. The quality of the formed microrelief and its influence on the stability of folding or clamping processes are not evaluated.

In [10], the authors investigate double ultrasonic burnishing of titanium blanks. Despite the positive results regarding improved fatigue strength, the article does not cover aspects related to relief ac-

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curacy, its reproducibility, or compatibility with narrow profiles and small radii.

Article [11] analyzes the reduction of surface roughness on shafts after ultrasonic burnishing. However, it does not consider any example of processing complex contours or radius-transition zones, which are typical for profiled components of bookbinding mechanisms and are characterized by complex geometry and localized intensive tribological loading.

Thus, despite the wide representation of studies devoted to ultrasonic burnishing with indenters, most of them focus on flat or cylindrical components, on hard materials (in particular, titanium and stainless steel), and are conducted under conditions different from those typical of printing production. The following aspects remain insufficiently explored:

— processing of profiled steel components with complex geometry;

— formation of microrelief with controlled orientation and period;

— assessment of wear resistance under interaction with paper or cardboard materials;

— influence of microrelief on the stability of folding, clamping, and sheet guiding.

These observations substantiate the relevance and novelty of the current study, which is aimed at investigating the effect of ultrasonic burnishing on the wear resistance of profiled components of bookbinding equipment, taking into account the specific features of their operation.

The purpose of this study is to provide a theoretical justification for the possibility of improving the wear resistance of profiled components in bookbinding equipment by forming a strengthening microrelief using the method of ultrasonic burnishing with a spherical indenter.

To achieve this purpose, the following research objectives are set:

1. To determine the conditions of operational wear of profiled components in bookbinding equipment and to analyze the feasibility of using ultrasonic burnishing as a method of localized surface layer strengthening.

2. To develop a numerical model of the ultrasonic burnishing process for the surface layer of a profiled steel component, taking into account contact interaction, vibration parameters, pressing force, and tool feed rate.

3. To assess the influence of processing parameters on stress and residual strain distribution, the depth of the strengthened layer, and the surface microgeometry formed as a result of plastic deformation.

4. To analyze the wear resistance of the formed surface using mathematical models of friction and wear, considering changes in roughness, residual stresses, and microrelief characteristics.

Methods

The aim of the theoretical study is to model the influence of ultrasonic burnishing on the formation of a strengthening microrelief on the surface of profiled steel components operating under contact friction conditions in the assemblies of bookbinding equipment. Particular attention is paid to determining the distribution of stresses and strains in the subsurface

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zone, evaluating the effective depth of strengthening, as well as identifying the relief parameters that ensure improved wear resistance during interaction with cardboard and paper-based materials.

The object of the study is a fragment of a profiled component featuring a geometry that includes a combination of flat and curved surfaces. The material used is structural carbon steel AISI 1045, with mechanical properties based on tabulated data:

— Young's modulus E = 210 GPa,
— Poisson's ratio ν = 0.3,
— Yield strength σ_y = 370 MPa.

Mathematical modeling of the microrelief formation process during ultrasonic burnishing was performed using the finite element method (FEM) in the ANSYS Mechanical software environment.

To ensure the reliability and relevance of the model to real processing conditions, the key input parameters were identified. These parameters characterize both the geometric features of the indenters and the physical and mechanical properties of the material being treated. They serve as the basis for constructing the contact interaction model and calculating the local stress–strain states in the ultrasonic impact zone. The generalized values of the initial data are presented in Table 1.

The simulation considered the contact interaction between a spherical hard-alloy indenter and the surface of a profiled component subjected to ultrasonic burnishing. The geometry of the working zone of the profiled component was adapted to match actual design parameters, taking into account local curvature and the contact nature of the loading. To ensure high accuracy in the contact zone, a refined finite element mesh was applied with an average element size of 0.1–0.2 mm.

The indenter was modeled as a perfectly rigid body, while the profiled component was defined as an elastic–plastic body capable of undergoing local residual defor-

Table 1

Initial parameters of the mathematical model of ultrasonic burnishing

Parameter	Symbol	Value	Unit
Diameter of spherical indenter	d	10	mm
Amplitude of ultrasonic vibrations	A	10–20	µm
Frequency of ultrasonic vibrations	f	20	kHz
Static pressing force	F	100–150	N
Feed rate of the indenter	v	50	mm/min
Young's modulus of AISI 1045 steel	E	210	GPa
Poisson's ratio	ν	0.3	—
Yield strength of steel	σ_y	370	MPa
Initial surface roughness	Ra	0.7	µm

mations, described using the von Mises yield criterion [12]. Boundary conditions were applied to the model to ensure the stability of the component's position and accurate reproduction of the burnishing conditions.

Ultrasonic loading was implemented as a combination of a static pressing force and a harmonic dynamic force simulating the effect of high-frequency vibrations of the indenter at a frequency of 20 kHz. Contact in the interaction zone was modeled with friction, according to the coefficient of friction μ specified in Table 1.

The simulation results were used to construct a modified model of local wear, taking into account the generated microrelief. Additionally, an analysis was carried out to determine the distribution of contact stresses, displacements, and potential zones of surface strengthening on the profiled component.

The effect of the formed microrelief on wear resistance was evaluated analytically by applying a modified model of contact interaction that incorporates the periodic surface texture. Wear behavior was described using equations that account for variations in surface roughness and residual stresses. For comparison purposes, two scenarios were simulated: one with a smooth surface and another with a microrelief structure based on FEM simulation results.

Results

Fig. 1 presents a functional diagram of the interaction between the ultrasonic burnishing tool and the surface of a profiled metallic component. The core element of the system is the tool (pos. 4), equipped with a spherical hard-alloy indenter (pos. 3), which receives high-frequency vibrations in the range of 20–40 kHz from a vibration generator. The working body maintains continuous contact with the treated surface.

The profiled component (pos. 1), characterized by a curvilinear geometry, is fixed in a position that

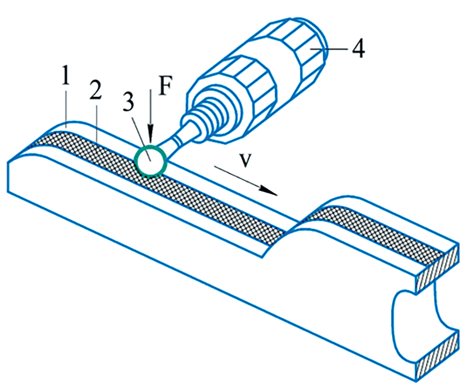

Fig. 1. Schematic of the local surface strengthening process for a profiled metallic component using ultrasonic burnishing with a spherical indenter: 1 — profiled component; 2 — deformation zone (contact area); 3 — spherical indenter; 4 — ultrasonic tool with vibratory drive; F — burnishing force; V — feed direction of the component

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provides access to the spherical indenter. The surface of the component is subjected to the combined action of static pressure (F), applied vertically downward, and vibrational energy transmitted from the tool.

During the feed motion of the spherical indenter along the surface of the profiled component at a given feed rate (V), plastic deformation occurs in the surface layer. In the contact zone (pos. 2), a densified microrelief is formed, characterized by reduced roughness and a wavy microstructure. This ensures localized surface strengthening without the application of elevated temperatures.

The formed microrelief reduces contact friction with paper or cardboard materials during operation and enhances wear resistance. This approach is particularly relevant for thin-walled or complex-profile components, where conventional hardening methods cannot be applied.

To quantitatively evaluate the effectiveness of the generated microrelief, analytical modeling of surface wear was performed for a profiled component under real operating contact conditions. For this purpose, both classical and modified approaches to wear modeling were used, allowing consideration of the influence of the strengthened surface layer, microgeometry, and mechanical properties of the surface.

One of the fundamental equations widely applied for wear prediction under sliding conditions is the Archard equation [9]. It establishes a quantitative relationship between the volume of worn material and the key parameters of contact interaction, including load, relative displacement, and material hardness. This relationship is expressed by the following formula:

$$dw = k \cdot \frac{p \cdot ds}{H}, \qquad (1)$$

where dw — incremental volume of worn material; k — wear coefficient (empirical parameter); p — contact pressure; ds — differential increment of sliding distance; H — material hardness.

The differential form of the Archard equation, adapted for use in numerical modeling (particularly FEM), enables the calculation of the local wear rate as a function of contact pressure, relative sliding velocity, and material hardness. This allows for dynamic updating of the contact surface geometry during iterative analysis.

$$dV = \frac{K}{H} p(x,t) \cdot v(x,t) \cdot dt \cdot dA, \qquad (2)$$

where dV — elementary wear volume on a surface element of area dA over a small time increment dt; K — wear coefficient (dimensionless); H — material hardness (Pa); p(x, t) — contact pressure at point x at time t (Pa); v(x, t) — relative sliding velocity at point x (m/s); dA — elemental area of the contact surface (m^2); dt — small time interval (s).

To transition from local analysis to a generalized evaluation of wear across the entire contact surface of the profiled component, the integral form of the equation was used. This form allows for the calculation of the total volume of material loss over a specified operating period. Such an approach enables the generalization of numerical modeling results and makes it possible to assess the effectiveness of surface strengthening across the entire working zone.

$$V=\int_0^T\int_A \frac{K}{H}\cdot p(x,t)\cdot v(x,t)\,dA\,dt. \quad (3)$$

To provide a more detailed description of local changes in the structure of the surface layer, the study transitions from a general integral approach to characteristics that account for the wear intensity at a specific point. The concept of wear density is further considered:

$$\frac{dw}{ds}=k\cdot\frac{p}{H}. \quad (4)$$

To obtain a more accurate assessment of the local wear of the surface of profiled steel components after ultrasonic burnishing, a modified model has been proposed. This model takes into account the surface microgeometry, residual stresses, and the spatial–temporal non-uniformity of the stress–strain state. It represents a development of the classical Archard model and is formalized as follows:

$$\dot{w}(x,t)=K\cdot\frac{p(x,t)\cdot v(x,t)}{H(x,t)}\cdot\left(1-\alpha\cdot R_q(x,t)+\beta\cdot\sigma_{res}(x,t)\right), \quad (5)$$

where w(x, t) — local wear rate at point x and time t ($m^3/m^2\cdot s$); K — wear coefficient dependent on the material pair in contact; p(x, t) — contact pressure (Pa); ν(x, t) — local relative sliding velocity (m/s); H(x, t) — local material hardness at point x (Pa); R_q(x, t) — root mean square roughness of the microrelief (m); σ_{res} (x, t) — residual stress after plastic deformation (Pa); α, β — empirical coefficients accounting for the influence of microrelief and residual stresses.

This model makes it possible to estimate the wear rate at each point on the surface, depending on the actual condition of the treated zone. The inclusion of microgeometry (via R_q) and residual stress (σ_{res}) enables a more accurate simulation of the operational durability of components treated using ultrasonic burnishing.

Unlike the classical Archard model, this modification allows for the prediction of the effectiveness of surface strengthening technologies, in particular by evaluating the influence of the induced microrelief and local plastic deformation on wear suppression.

For the full implementation of the wear model, it is necessary to describe the contact interaction between the spherical indenter and the surface of the profiled component. One of the key parameters in this context is the distribution of contact pressure, which determines the intensity of local loading and, consequently, the wear rate within the contact zone.

Let p(x) denote the distribution of normal contact stress along the x coordinate within the contact area between the spherical indenter and the surface of the profiled component. For Hertzian-type contact between a spherical indenter and the component:

$$p(x)=p_0\cdot\sqrt{1-\left(\frac{x}{a}\right)^2},\quad |x|\le a, \quad (6)$$

where p_0 — maximum contact pressure; a — half-width of the contact area.

Then:

$$\frac{dw(x)}{ds}=k\cdot\frac{p(x)}{H}= =k\cdot\frac{p_0}{H}\cdot\sqrt{1-\left(\frac{x}{a}\right)^2}. \quad (7)$$

By integrating over the entire contact length:

$$w=\int_{-a}^{a}\frac{dw(x)}{ds}dx= =\int_{-a}^{a}k\cdot\frac{p_0}{H}\cdot\sqrt{1-\left(\frac{x}{a}\right)^2}dx. \quad (8)$$

Substituting $x = a\sin\theta$, $dx = a\cos\theta d\theta$, yields:

$$w=k\cdot\frac{p_0}{H}\cdot a\int_{-\pi/2}^{\pi/2}\cos^2\theta d\theta= =k\cdot\frac{p_0}{H}\cdot a\cdot\pi. \quad (9)$$

This variable substitution simplifies the integration process, which is particularly convenient for numerical or analytical solutions, especially under conditions of Hertzian contact symmetry.

Thus, the development of the contact pressure distribution model using classical Hertzian approaches and their mathematical transformation provides a fundamental basis for further analysis of friction and wear parameter changes during the implementation of surface strengthening technologies.

Based on the derived analytical relationships, it becomes possible to assess how ultrasonic burnishing influences the physico-mechanical properties of the contact zone.

Ultrasonic burnishing affects the following characteristics:

— hardness $H \to H' > H$,

— coefficient of friction $\mu \to \mu' < \mu$,

— pressure distribution becomes more uniform, thereby reducing peak contact stresses $p_0 \to p_0 < p_0$.

Therefore:

$$w'=k'\cdot\frac{p_0'}{H'}\cdot a\cdot\pi<w. \quad (10)$$

==> As a result, the overall wear is reduced after ultrasonic burnishing.

A generalization of the effect of ultrasonic burnishing on the parameters of contact interaction confirms its positive influence in the context of wear reduction. For a deeper understanding of the underlying mechanism, it is appropriate to perform a differential analysis that enables a quantitative evaluation of wear variation as a function of key factors — primarily, material hardness.

A differential justification of the effectiveness of ultrasonic burnishing in improving wear resistance involves analyzing the dependence of wear on hardness, which can be expressed in the form of a corresponding derivative:

$$\frac{d}{dH}\left(\frac{dw}{ds}\right)= =-k\cdot\frac{p}{H^2}<0. \quad (11)$$

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The differential analysis demonstrates that an increase in surface hardness as a result of ultrasonic burnishing leads to a reduction in the wear rate. Additionally, the decrease in the coefficient of friction and the leveling of the surface microgeometry contribute to a more uniform load distribution, which confirms the feasibility of using this method to enhance the durability of profiled components.

The results of the numerical model of the ultrasonic burnishing process for a profiled steel component, considering contact interaction, vibration parameters, applied force, and feed rate of the tool, include:

1. Contact pressure:

$$p = \frac{F}{A}, \qquad (12)$$

where F — the applied normal force and A is the contact area.

2. Vibrational force component:

$$F_{vib} = A_{vib} \cdot \sin(\omega), \qquad (13)$$

where A_{vib} — the vibration amplitude and ω is the angular frequency.

3. Total force considering vibration:

$$F_{total} = F + A_{vib} \cdot \sin(w). \qquad (14)$$

4. Relative deformation (strain), according to Hooke's law:

$$\varepsilon = \frac{F_{total}}{A \cdot E} = \frac{A_{vib} \cdot \sin(w)}{A \cdot E}, \qquad (15)$$

where E — the modulus of elasticity (Young's modulus).

5. Condition for the onset of plastic deformation:

$$\frac{F + A_{vib} \cdot \sin(w)}{A} \geq \sigma_y, \qquad (16)$$

where σ_y — the yield strength of the material.

The resulting system of equations enables a comprehensive analysis of the conditions under which local plastic deformation occurs in the surface layer of the profiled component. In particular, it makes it possible to determine the parameters of the ultrasonic burnishing process — such as contact force, vibration amplitude, and vibration frequency — at which the formation of microrelief begins. Moreover, by solving this system, it is possible to quantitatively estimate the level of contact pressure and to evaluate the influence of vibration parameters on the improvement of the geometric characteristics of the microrelief.

To illustrate the strengthening dynamics of the surface layer under different ultrasonic burnishing forces, a graph was constructed showing the dependence of relative strain on time under varying loading conditions applied by the spherical indenter. This approach allows for visualizing the effect of contact force on the intensity of plastic deformation and the development of microrelief during processing (Fig. 2).

The graph (Fig. 2) illustrates the dependence of the relative strain of the surface layer of a steel profiled plate on time under different contact forces during ultrasonic rolling. For each applied force (10 N, 30 N, 50 N), the corresponding sinusoidal variation in strain is shown, resulting from tool vibrations at a frequency of 20 kHz. The amplitude

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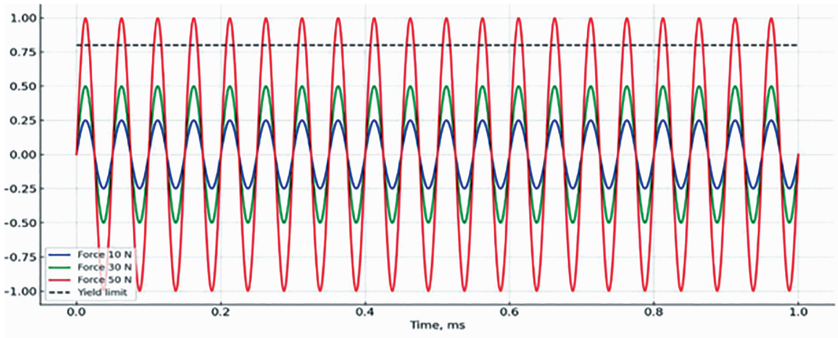

Fig. 2. Dependence of the relative strain of the surface layer on time under different ultrasonic rolling forces applied by a spherical indenter (10 N, 30 N, 50 N)

of strain oscillations increases with the rise in contact force, indicating more intensive plastic deformation of the material. The dashed horizontal line marks the conventional yield limit. The intersection of the strain curves with this line indicates the onset of residual deformation accumulation, which contributes to surface strengthening.

The graph (Fig. 3) presents the dynamics of the tool feed rate (blue curve) and the corresponding changes in impact energy (orange curve) throughout the ultrasonic rolling process of a profiled element.

The increase in feed rate simulates the gradual acceleration of the working body, which is accompanied by a quadratic rise in energy according to the following law:

$$E = \frac{1}{2}mv^2, \qquad (17)$$

where E — impact energy; m — mass of the tool (or the equivalent mass of the contact section); ν — instantaneous feed velocity of the tool in the direction of deformation.

During the operation of the generator producing high-frequency

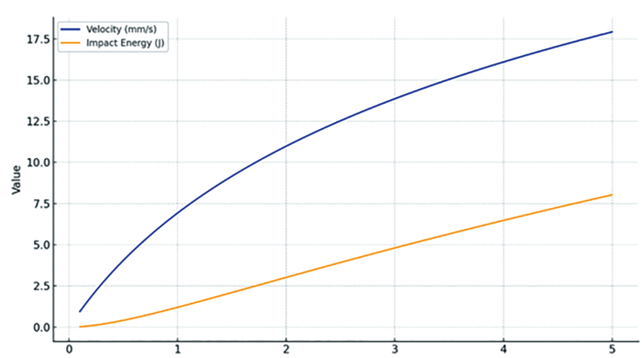

Fig. 3. Dependence of tool feed rate and impact energy on time during the ultrasonic burnishing of a profiled component

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oscillations, the feed velocity of the tool varies depending on the technological settings, vibration amplitude, and frequency. Accordingly, the impact energy, which determines the depth of plastic deformation, also changes.

Thus, a direct quadratic dependence of energy on feed velocity is observed. This means that even a slight increase in feed speed causes a significant rise in the energy transmitted per unit of time, which must be taken into account when modeling the contact interaction in FEM systems.

This behavior of the process parameters allows for evaluating the influence of dynamic action on the surface layer of the processed material and identifying effective strengthening modes without exceeding the permissible load threshold.

To describe the influence of ultrasonic burnishing parameters on the stress–strain state, strengthening depth, and surface microgeometry, a differential calculus formalism was used that accounts for local spatial (depth-wise and surface coordinate) and temporal variations during tool contact.

Depending on the pressing force F, indenter geometry, and material properties, the local contact stress σ was calculated using a modified Hertz equation and can be expressed in differential form as:

$$\frac{\partial\sigma}{\partial x}=f_1(F,R,E,\nu,x), \qquad (18)$$

where x — coordinate along the surface of the workpiece; R — indenter radius; E — Young's modulus and Poisson's ratio; f_1 — stress distribution function accounting for the shape of the contacting body.

Plastic deformation in the subsurface layer occurs when the stress exceeds the yield strength σ_y:

$$\varepsilon(x,z,t)= = \int_0^t \frac{\sigma(x,z,\tau)-\sigma y}{E}\cdot \cdot H(\sigma-\sigma y)d\tau, \qquad (19)$$

where z — depth from the surface; t — processing time; H(·) — Heaviside function, accounting for the plasticity condition.

The Heaviside function [13, 14] (unit step function) in the model of microrelief formation during ultrasonic burnishing acts as a conditional switch that considers only the effective contact periods when the contact pressure exceeds the plastic deformation threshold. It allows exclusion from the calculations of the phases in which no plastic strengthening occurs, thereby enabling a more accurate description of the dynamics of deformation accumulation and local wear. Thus, the Heaviside function enhances the accuracy of the simulation by filtering out the ineffective components of the vibrational load.

The strengthening depth is defined as the region where residual plastic deformations exceed the threshold value ε_{min}:

$$hs(x) = \max\{z:\varepsilon(x, z) \ge \varepsilon min\}. \qquad (20)$$

The change in surface profile due to plastic deformation is determined by the integral of local material subsidence:

$$h(x)=h_0(x)- -\int_o^z \varepsilon(x,z)dz, \qquad (21)$$

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where $h_0(x)$ — the initial surface profile (before processing). The residual stresses in the model are calculated based on the balance between elastic and plastic deformations:

$$\frac{d\sigma_{res}(z)}{dz} = + \frac{E}{1-\nu^2} \cdot \frac{d^2u(z)}{dz^2}, \quad (22)$$

where u(z) is the displacement of material elements at depth z, determined by the prior action of the indenter.

Thus, mathematical relationships (20)–(22) enable a quantitative description of the influence of ultrasonic burnishing on microstructural changes in the subsurface zone of the profiled part. Special attention is given to the evaluation of the residual stress distribution formed as a result of localized plastic settlement of the material under the indenter load.

To visualize the modeling results, a graph of the residual stress variation in the direction of depth from the treated surface was constructed (Fig. 4).

This graph (Fig. 4) illustrates the variation of normal residual stress (σ) along the depth from the treated surface of the profiled component. The results indicate that in the near-surface zone (up to 0.05 mm), a peak compressive residual stress is observed, which gradually decreases with increasing depth. This type of distribution is typical for cold plastic deformation processes, particularly ultrasonic burnishing, and contributes to the formation of a hardened layer with enhanced fatigue and wear resistance. With increasing depth, the stress approaches zero, indicating the boundary of the deformation-affected zone.

To evaluate the effect of the ultrasonic burnishing process on the surface microrelief, a graph was constructed to show the variation in microprofile depth along the cross-section of the part (Fig. 5).

The graph (Fig. 5) shows the variation in the surface microgeometry of the profiled component along the depth direction after treatment using ultrasonic burnishing with a spherical indenter. The

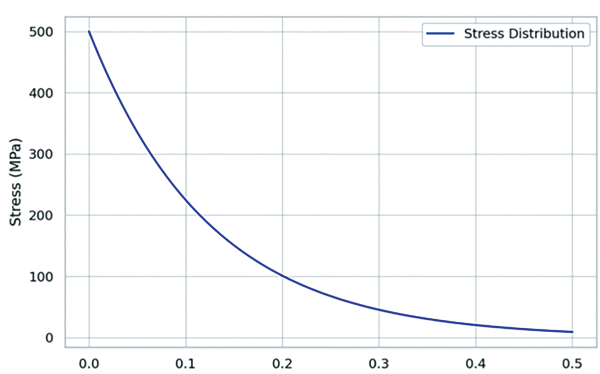

Fig. 4. Residual stress distribution along the depth of the treated layer of the profiled part after ultrasonic burnishing

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X-axis represents the indentation depth (Depth, mm), while the Y-axis indicates the values of surface microirregularities (Microgeometry, μm), characterizing the wavy relief of the surface.

In the upper section of the graph, harmonic oscillations of the microprofile are observed, with amplitudes gradually decreasing with depth. This indicates that the influence of vibration is most intense at the surface and decays progressively with increasing depth. Such a pattern is typical for localized plastic deformation induced by ultrasonic oscillations, enabling the formation of a hardened wavy microrelief that improves the operational performance of the treated surface — particularly wear resistance and friction characteristics.

Analytical modeling has shown that the application of ultrasonic vibrations during burnishing significantly alters the distribution of residual stresses and the microgeometry of the subsurface zone of the profiled component. Table 2 presents the results of theoretical calculations regarding the influence of vibrational loading on the parameters of the surface layer, based on numerical analysis performed in the ANSYS environment.

Analysis of the data indicates that as a result of the simulation, the residual stress on the surface of the profiled component under ultrasonic loading increases from 300 MPa to 320 MPa, indicating an intensification of plastic deformation and material strengthening. With increasing depth from the surface, the stress gradually decreases; however, at all calculated levels (up to 0.5 mm), it remains higher compared to the case without ultrasonic influence, indicating a deeper hardening effect. Simultaneously, a consistent reduction in surface roughness is observed under ultrasonic loading — from 1.2 μm to 0.122 μm — which reflects an improvement in surface microgeometry and, consequently, enhanced potential wear resistance.

To achieve a more accurate interpretation of the effect of ultrasonic burnishing, it is necessary to consider the nature of the dynamic loading acting on the contact zone during processing. Ultrasonic

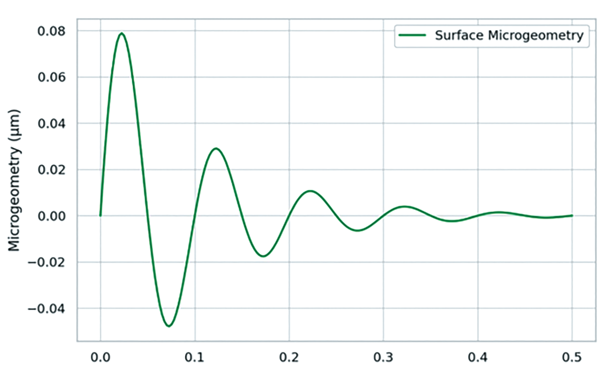

Fig. 5. Surface microgeometry profile as a function of depth after ultrasonic surface burnishing

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oscillations significantly alter the mechanics of contact interaction: they increase the intensity of local plastic deformation, promote a more uniform pressure distribution, and generate a microrelief with improved geometrical characteristics. Therefore, to construct a reliable mathematical model of surface strengthening, it is essential to integrate ultrasonic parameters into the corresponding equations.

In particular, the variable contact force should be represented as a time-dependent function F(t), which reflects the amplitude, frequency, and phase of ultrasonic oscillations acting in the contact zone between the indenter and the workpiece.

During the simulation, it was taken into account that ultrasonic loading generates high-frequency oscillations of the indenter at a frequency f (e.g., 20–40 kHz), resulting in the emergence of a time-varying contact force:

$$F(t) = F_0 + \Delta F \cdot \sin(2\pi f t). \quad (23)$$

The resulting expression for the force was substituted into all equations where the variable F is involved, in particular into:

— the equation for stress calculation;

— the equation for determining plastic deformation.

Each contact impulse from ultrasonic vibration acts as a short-term micro-load. In FEM-based simulations, this is accounted for through cyclic micro-impacts, which cumulatively generate plastic deformation:

$$\varepsilon_{total}(x,z,t) = \sum_{i=1}^{N} \varepsilon_{pulse}^{(i)}(x,z), \quad (24)$$

Table 2

Influence of ultrasonic vibrations on the distribution of residual stresses and microgeometry of the surface layer of the profiled component

Depth (mm)	Stress without vibration (MPa)	Stress with vibration (MPa)	Surface roughness without vibration (μm)	Surface roughness with vibration (μm)
0.0	300.0	320.0	1.2	0.9
0.056	227.24	229.29	1.016	0.721
0.111	172.13	164.29	0.86	0.577
0.167	130.38	117.72	0.728	0.462
0.222	98.76	84.35	0.616	0.37
0.278	74.81	60.44	0.522	0.296
0.333	56.66	43.31	0.441	0.237
0.389	42.92	31.03	0.374	0.19
0.444	32.51	22.23	0.316	0.152
0.5	24.63	15.93	0.268	0.122

where N — the number of impulses during time t.

Given the complexity of real-time numerical modeling of high-frequency vibrations, an equivalent average force was applied:

$$F_{eq}=F_0+\frac{1}{T}\int_0^T \Delta F\cdot\sin(2\pi ft)\,dt=F_0,$$

$$\text{(because } \int \sin=0 \text{),} \qquad (25)$$

To account for the influence of ultrasonic vibrations on the stress–strain state, a correction coefficient η was introduced into the calculated stress value:

$$\sigma_{eff}=\eta\cdot\sigma(F_0), \qquad (26)$$

where η — accounts for the local increase in deformation due to vibration. Thus, the combination of the equivalent force approach and the correction coefficient enables an adequate consideration of the accumulated effect of ultrasonic impulses on the plastic deformation of the material's surface layer. Taking these adjustments into account, a generalized equation can be formulated to describe the evolution of plastic deformation in the surface layer of a profiled steel component under ultrasonic vibration:

$$\varepsilon(x,z,t)= =\int_0^t \frac{F_0+\Delta F\cdot\sin(2\pi f\tau)-\sigma_y}{A\cdot E}\cdot \cdot H(F(\tau)-Fy)\,d\tau. \qquad (27)$$

The proposed study confirmed the effectiveness of ultrasonic burnishing as a method for forming a strengthening microrelief on profiled components of bookbinding equipment to enhance their wear resistance. Numerical modeling was conducted for profiled components made of AISI 1045 steel. A hard-alloy spherical indenter was applied to the surface under load and subjected to pulsed ultrasonic vibrations.

A mathematical model of the contact interaction was developed, taking into account residual stresses and surface microgeometry. This model made it possible to evaluate wear intensity using both classical and modified friction laws. The results of the numerical modeling can be used to develop technological guidelines for surface treatment and to predict the service life of components in printing production. Future research will focus on the experimental validation of the formed microrelief and the investigation of its influence on performance characteristics under real operating conditions of bookbinding systems.

Discussion

The results of the numerical analysis of the ultrasonic burnishing process applied to the surface of profiled components made of AISI 1045 steel confirm the feasibility of forming a strengthening microrelief in the near-surface layer. The obtained distributions of residual stresses, plastic deformations, and changes in surface microgeometry correspond to the known patterns of high-frequency loading effects on metallic structures, particularly the formation of a wavy structure typical for vibratory strengthening processes.

Unlike classical approaches that are primarily focused on macroscopic friction parameters, the proposed study implements an analytical-

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numerical model combining residual stress evaluation, surface roughness parameters, and local hardness with wear prediction using a modified local wear model that incorporates the effects of microrelief. This approach enables a comprehensive assessment of the wear resistance of working surfaces of profiled components under variable frictional conditions. This is especially relevant for printing equipment, where components are subjected to cyclic mechanical loading during contact with paper and cardboard materials.

A comparison of the results obtained using the classical Archard model and the developed modified model of local wear revealed a significant reduction in wear rate in cases where a microrelief with a hardened layer was pre-formed. In particular, the adaptation of the Archard model for numerical implementation made it possible to transition from an integral to a differential formulation, accounting for the local distribution of load, hardness, and surface roughness. The incorporation of residual stress (σ_{res}) and the microrelief parameter (R_q) into the model increased its sensitivity to local variations in contact geometry.

The obtained relationships are consistent with findings reported in the literature [5, 10], which highlight the positive effect of compressive residual stresses on the tribological performance of surfaces. The proposed model demonstrated a higher sensitivity to microgeometry variations and provided a more accurate representation of real operating conditions compared to the simplified Archard approach.

Numerical results were obtained in the ANSYS Mechanical environment using the finite element method (FEM), enabling precise simulation of plastic strain accumulation and residual stress distribution in the surface layer of the profiled component. The simulation results show that the wavy microrelief not only reduces contact friction but also promotes the localization of residual compressive stresses in the near-surface zone, which has a beneficial effect on wear resistance.

The obtained graphs (Figs. 4, 5) confirm the characteristic distribution of residual stresses and the formation of the microrelief resulting from ultrasonic burnishing with a spherical indenter. The spherical indenter enables concentrated localization of load, facilitating the formation of a wavy microrelief structure that enhances wear resistance and reduces the coefficient of friction.

The scientific novelty of this study lies in the development of a numerical-analytical model of the ultrasonic burnishing process that simultaneously accounts for the influence of the formed microrelief, residual stresses, and wear parameters. This approach provides a comprehensive assessment of the durability of profiled component surfaces and can be used to predict the service life of elements in bookbinding equipment.

At the same time, certain limitations of the theoretical model should be acknowledged. It is based on the assumption of material isotropy and homogeneity, which does not take into account potential effects of structural anisotropy induced by cold plastic deformation. The computational scheme does not consider thermal effects, although local heating due to intensive friction may occur, which could affect the structure and hardness of the hardened layer. The lack of experimental validation limits the complete verification of the theoretical assumptions under real operating conditions. These limitations can be addressed in future work through experimental investigations and the incorporation of advanced physical models of the material.

Conclusions

1. The operational wear characteristics of profiled components of bookbinding equipment operating under contact friction and vibration conditions have been identified. The feasibility of applying ultrasonic surface rolling as an effective method of local surface strengthening without thermal influence has been substantiated.

2. A numerical model of the ultrasonic surface rolling process for profiled components made of AISI 1045 steel has been developed, taking into account the geometry of the spherical indenter, vibration parameters, contact force, and feed rate. The model is implemented using the finite element method, allowing for the determination of the stress–strain state, surface microgeometry, and strengthening depth.

3. Based on the simulation results, it was established that an increase in the contact force and vibration amplitude of the spherical indenter promotes more intensive formation of plastic deformations in the subsurface layer of the profiled components, increases residual stresses, and reduces surface roughness. The formed wavy microrelief contributes to a reduction in the friction coefficient and improves the stability of contact interaction with binding materials, signatures, and printing semi-finished products.

4. The application of the modified Archard wear model for comparative analysis showed that a surface with a microrelief formed by ultrasonic rolling exhibits lower wear rates compared to a smooth surface. This confirms the effectiveness of the method for improving the wear resistance of profiled components in bookbinding systems.

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Об'єктом дослідження є процеси підвищення зносостійкості профільних деталей брошурувального обладнання шляхом формування зміцнювального мікрорельєфу методом ультразвукового накатування. Розглянуто моделі контактної взаємодії сферичного індентора з поверхнею сталевих деталей для визначення закономірностей утворення мікрорельєфу та його впливу на зносостійкість. Проведене дослідження має аналітичний та теоретичний характер і базується на математичному моделюванні контактного навантаження, мікропластичної деформації та параметрів шорсткості поверхні, що формуються внаслідок ультразвукового накатування.

Ключові слова: зносостійкість; математичне моделювання; мікрорельєф; ультразвукове накатування; індентор; залишкові напруження; профільні сталеві деталі; модифікована модель зносу.

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