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DETERMINING OF THE EFFECT OF REINFORCING MICRORELIEF GUIDES ON THE EFFICIENCY OF FOLDING INTEGRATED COVERS

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The object of research is the processes of strengthening the working surfaces of profile folding strips made of stainless steel AISI 347 and carbon steel AISI 1005 using laser formation of microrelief guides. The analytical and experimental studies are based on the technique of laser microrelief formation by pulsed laser effects. The main assumption of the study is that the use of laser microrelief formation could increase the hardness and wear resistance of the folding strips, improving the process of folding integrated covers. Analyzing the effect of different hardening methods on the mechanical properties and wear resistance of the working surfaces of folding strips is necessary to achieve this goal. A methodology for assessing microstructural changes and their impact on the mechanical properties of folding strips during laser hardening has been proposed. It has been shown that the formation of microrelief guides by laser pulse exposure reduces the thermal load on the material, increases the uniformity of hardening and wear resistance. The revealed wear rates calculated for carbon steel AISI 1005 are 0.875, and for stainless steel AISI 347 – 0.345. To improve the accuracy and efficiency of the folding process, a methodology has been devised for calculating the quantitative formation of microrelief guides on the working surface of profile folding strips. This will not only improve the wear resistance and mechanical properties of the strips but also optimize production processes. Differences in the results of hardening for stainless steel AISI 347 and carbon steel AISI 1005 were found: the hardness values for AISI 347 are 3,088–4,904 MPa at a load of 50–350 g with a deviation of 37.1 %, and for AISI 1005 – 2141–1665 MPa with a deviation of 22.3 %

Keywords: integrated covers, optimal parameters of pulsed laser radiation, strengthening of folding strips, microrelief guides, microstructural changes in the material

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1. Introduction

High-quality production of integrated covers is the basis for durability and attractiveness of book and journal products. Integrated covers of carved chrome ersatz sweep provide high strength and aesthetic quality. An important stage in the formation of covers is gluing the flaps to the base on a high-speed folding and gluing line, which predetermines the contour geometric accuracy and strength of the cover design. Folding of flaps with the help of profile strips enables accurate bending without damage to the material, which affects the accuracy and service life of the covers.

Folding strips are made of different materials [1], in particular AISI (American Iron and Steel Institute) 347 stainless steel and AISI 1005 carbon steel for general engineering applications. These materials have different physical and mechanical properties that affect their performance characteristics, such as such as wear resistance, hardness, and resistance to mechanical loads. Stainless steel is characterized by high corrosion resistance and moderate hardness, while carbon steel for general engineering applications AISI 1005, having high mechanical strength, requires additional protection against corrosion. Surface strengthening methods are used to improve the working characteristics of folding strips, which makes it possible to significantly increase their durability and resistance to wear.

One of the promising strengthening methods is the laser formation of microrelief guides. This method makes it possible to create a microrelief on the surface of the material, which not only increases hardness and wear resistance. It also improves the folding process due to the reduction of the friction coefficient and uniform distribution of loads. Laser point formation of microrelief by successive bursts of a laser beam ensures precise control over the strengthening process and enables adaptation of processing parameters depending on the properties of the processed material.

Evaluation of the impact of reinforcing microrelief guides on the folding process of covers made of AISI 347 and AISI 1005 reveals changes in the mechanical properties of the materials. In particular, there is an increase in strength, an improvement in wear resistance, and a reduction in the coefficient of friction, which contributes to the optimization of production processes and the improvement of the quality of final products.

Research aimed at improving the folding process directly affects the final quality of products. Optimizing folding technologies could significantly increase productivity and reduce production costs. One of the promising methods is the laser formation of microrelief guides, which is an advanced technology that makes it possible to increase hardness, wear resistance, and control over the process of strengthening materials. These innovative approaches can be applied in various industries, making them important for printing applications.

Increasing the wear resistance of folding strips leads to a decrease in the frequency of their replacement and maintenance, which reduces operating costs and downtime of production equipment. Research in this area brings together different fields of science and technology, including materials science, laser technology, mechanics, and printing, which contributes to the development of interdisciplinary knowledge and technology. Improving the quality and durability of integrated covers increases the competitiveness of printed products on the market, which is important for publishers and manufacturers.

The results of such research could be implemented in the printing industry to improve existing technological processes and devise new production methods, which increases their practical value. Therefore, the research relevance is predetermined by the need to improve the quality and durability of printed articles, as well as the development of innovative technologies for strengthening folding strips.

2. Literature review and problem statement

The quality of the folding process of integrated covers and their durability is affected by a number of factors, in particular, the use of reinforcing micro-relief guides integrated into the working surface of the profile folding strips. These guides increase resistance to mechanical loads and reduce the risk of defects of integrated covers during operation. The formation of the micro-relief structure of strips contributes to the uniform distribution of stress during the bending of the flaps of covers. In addition to mechanical techniques, innovative technologies of laser processing, plasma sputtering, and ion-plasma strengthening can be used to strengthen the surface of profile folding strips.

Paper [2] discusses the basics and mechanisms for improving the wear resistance of metallic materials using LSP (Laser Shock Peening). The authors analyze the effect of laser irradiation on the microstructure and mechanical properties of metals. The research findings demonstrate a significant reduction in wear and increased durability of the treated materials. However, the study did not consider the issues that arise during the formation of the profile of folding strips and the possible risks of partial destruction of the surface layer after the application of LSP technology.

Work [3] reports the study of wear resistance of AISI 9310 steel after micro-laser shock hardening (Micro-LSP). The authors established that the use of this technology makes it possible to significantly increase the hardness and wear resistance of steel. Studies show that the treatment improves the durability of the material under high loads. However, the possibility of applying the Micro-LSP technology to modify the surface of stainless steel parts, which is used for the manufacture of folding strips, was not investigated in the paper. Study [4] reveals the influence of multiple laser hardening LPwC (Laser Peening without Coating) on microstructural Fatigue and fretting wear behavior of austenitic stainless steel. The results show a significant improvement in the mechanical properties and wear resistance of the material after treatment. The authors note that the technology enables uniform strengthening and reduces the risk of microcracks. After applying the LPwC technology, the microhardness of the stainless steel surface increases but the possible negative changes of the strengthened surface after changing the profile of the folding strips are not taken into account.

Paper [5] describes the combined application of laser transformation hardening and ultrasonic shock deformation to improve the wear resistance of AISI 1045 steel. The authors established that the synergistic effect of both methods allows achieving high hardness and wear resistance indicators. The proposed technique significantly improves the operational characteristics of steel. However, the preservation of the identity of the surface profile of the part after laser heat treatment has not been determined. Studt [6] examines the microstructure and wear resistance of CrCoNi coatings obtained by the method of laser surfacing with additional treatment by ultrasonic exposure. The authors found that the combined treatment provides high uniformity and improves the mechanical properties of the coatings. The results of the study confirm a significant reduction in wear and increased durability of the material. However, the research did not consider the conditions for maintaining the stability of the strengthened surface layer when the temperature increases, which occurs as a result of friction during operation under intensive conditions.

Work [7] reports the latest achievements in the field of laser surface transformation strengthening of industrial metals. The authors analyze the influence of various processing parameters on the mechanical properties of materials. Studies show that the application of this technology significantly improves the hardness and wear resistance of strengthened components. However, questions regarding the long-term stability of these properties under conditions of high operating loads remain open. Study [8] highlights the results of hybrid micro texture research as a multi-scale approach to surface engineering to improve tribological characteristics. The authors demonstrate that the use of micro textures makes it possible to reduce the coefficient of friction and wear of materials. The study includes an analysis of the effectiveness of various types of micro textures in increasing the durability and reliability of engineering components. At the same time, the research does not establish a clear relationship between the reduction of the friction coefficient and the increase in the wear resistance of the strengthened surface to understand the influence of microstructures on the operational characteristics of parts.

Paper [9] investigates the relationship between surface texture parameters and tribological behavior of four metal materials with laser surface texturing (LST). The authors found that the optimal texturing parameters make it possible to significantly reduce wear and improve the mechanical properties of materials. However, it has not been determined how these textured surfaces would behave in wet or corrosive environments, which is an important aspect for their practical application in cover manufacturing. Work [10] reports a comparative study of various overlaps during diode laser hardening of low-carbon steel and stainless steel. The authors analyze the effect of various overlays on the mechanical properties and wear resistance of the treated materials. Studies show that optimal overlapping parameters make it possible to achieve better results in increasing the hardness and durability of steel.

Paper [11] examines the effect of laser surface remelting on the microstructure, mechanical properties, and tribological characteristics of metals and alloys. The authors summarize the results of numerous studies, demonstrating improvement in hardness, wear resistance, and friction reduction of treated materials. The paper emphasizes the importance of laser remelting as an effective method for increasing the durability of engineering components. At the same time, there are no detailed studies on the advantages of methods of strengthening the surface layer, which do not change its profile, as stated in [10, 11]. Study [12] presents an overview of methods of laser hardening of surfaces of aluminum alloys and composites. The authors analyze the effect of laser processing on the mechanical properties and wear resistance of materials. Research shows that laser technology can significantly improve the hardness and durability of aluminum alloys, making them more suitable for industrial applications. However, not all types of aluminum alloys respond equally to laser processing, and some of them may show insufficient stability, which leads to the appearance of microcracks during operation under conditions of high loads.

All this gives reason to assert the expediency of conducting research on the use of laser technologies for the formation of microrelief guides, which could contribute to increasing the hardness and wear resistance of the working surfaces of profile folding strips. This would help improve the quality of folding book and journal integrated covers due to the reduction of the friction coefficient and the risk of microcracks.

3. The aim and objectives of the study

The purpose of our study is to determine the influence of reinforcing microrelief guides integrated into the working surface of the folding strips on the quality of the folding process of integrated book and journal covers. This will make it possible to devise improved methods and technical recommendations aimed at increasing the hardness, wear resistance, and overall effectiveness of profile folding strips.

To achieve the goal, the following tasks were set:

– to carry out analysis and modeling of the process of improving the working surfaces of folding strips treated with a laser beam to create microrelief guides;

– to devise a procedure for detecting dimensional indicators of wear of the working surface and to determine the optimal parameters of laser hardening, which ensure an increase in surface hardness, a reduction in the coefficient of friction, and an improvement in wear resistance;

– to compare the physical-chemical processes of strengthening and wear resistance of profile folding strips made of stainless steel AISI 347 and carbon steel AISI 1005.

4. The study materials and methods

The object of our study is the process of strengthening the working surfaces of profile folding strips, processed with a laser beam to form microrelief guides. These strips are used for folding flaps of book-journal integrated covers. The research is based on analytical and experimental approaches, including the analysis of microstructural changes of materials after laser processing and the evaluation of their mechanical properties. The main hypothesis of the study assumes that the use of laser hardening to form micro-relief guides on the working surfaces of AISI 347 stainless steel and AISI 1005 carbon steel folding strips could improve their mechanical properties. In particular, this applies to indicators such as hardness, wear resistance, and reduction of the coefficient of friction.

The assumptions adopted in the work relate to the laser strengthening of the surface of the folding strips, which is achieved by forming microrelief guides that improve the mechanical properties of the surface. In particular, the optimal shape of these micro-relief guides reduces the coefficient of friction, which, in turn, increases the wear resistance of the material. In addition, the use of stainless steel AISI 347 and carbon steel AISI 1005 ensures sufficient strength and durability of the folding strips, which is important for their long-term operation in engineering applications.

Simplifications adopted in the work:

– microrelief guides can be described using simplified geometric models;

– the influence of microrelief guides on mechanical properties is considered under conditions of ideal contact between materials;

– the influence of thermal effects of laser radiation on the microstructure of the material is simplified to basic parameters (energy density, temperature change);

– it is accepted that hardness and wear resistance are linear functions of laser hardening parameters.

For the purpose of the study, profile folding strips were made of stainless steel AISI (American Iron and Steel Institute) 347 and carbon steel for general engineering applications AISI 1005. To apply microrelief guides on the samples of strips, a fiber laser GENERATOR G-Om-16-1 (Ukraine) was used, which is capable of generating high-quality laser radiation for high-precision technological processes. The wavelength of laser radiation is 1064 nm, which corresponds to the infrared range. The maximum power of the laser reaches 500 W, and the operating modes include continuous and pulse mode up to 20 W. The pulse duration varies from 10 to 200 ns, and the pulse power can reach 1 mJ. The size of the laser focus spot is from 30 to 100 microns. During the study, experiments were conducted on laser strengthening of folding strips using different modes of laser processing.

Evaluation of microstructural changes was carried out using modern methods of analysis, such as scanning electron microscopy (SEM) with an energy dispersive spectrometer (EDS detector). A scanning electron microscope, model JEOL JSM-7500F (JEOL Ltd, Japan), was used to obtain images that correspond to the parameters of our studies. The main characteristics of the microscope include a working distance of 1 to 50 mm, an acceleration voltage of 0.5 to 30 kV, and the possibility of magnification from 10× to 1,000,000×. The measurement range is from nanometers (nm) to millimeters (mm).

Measurement of the hardness and wear resistance of the strengthened surfaces of the folding strips samples was carried out by Vickers methods using a ZwickRoell microhardness meter (Germany). The device uses a diamond indentation tool in the shape of a tetrahedral pyramid to accurately determine hardness. Measurements were carried out at low loads: 50 g, 100 g, 150 g, 200 g, 250 g, 300 g, and 350 g, which allows obtaining detailed results about the mechanical properties of the samples. The results made it possible to identify differences in the behavior of the presented steel samples during laser processing, as well as to evaluate the influence of microrelief guides on the folding process.

Statistical data processing was carried out to process the results and analyze the change in the hardness of the folding strips depending on load. The main stages of this processing involved the formulation of recommendations regarding optimal loads when using folding strips under various operating conditions.

The main stages of statistical data processing:

1. Build a table: entering all the collected data into a table.
2. Compute descriptive statistics: determine the mean, standard deviation, minimum, maximum, median, and quartiles for each column of data.

Average value:

$$\bar{x} = \frac{1}{n}\sum_{i=1}^{n} x_i.$$

Standard deviation:

$$\sigma = \sqrt{\frac{1}{n-1}\sum_{i=1}^{n}\left(x_i - \bar{x}\right)^2}.$$

3. Construct plots of the dependence of hardness on load for visualization of the trend:

– scatter plot: plotting points (load, hardness) on the coordinate plane;

– adding a trend line for a visual representation of the dependence.

4. Carry out regression analysis to determine the mathematical model of the dependence of hardness on load.

5. Build a model: use linear regression to build a model:

– regression equation. Find the coefficients of the regression equation:

$$y = \beta_0 + \beta_1 x;$$

– assess the model's accuracy. Determine the coefficient of determination (R-squared) and perform statistical tests to assess the reliability of the R-squared model:

$$R^2 = \frac{\sum_{i=1}^{n}\left(\hat{y}_i - \bar{y}\right)^2}{\sum_{i=1}^{n}\left(y_i - \bar{y}\right)^2}.$$

6. Interpret results:

– analyze changes in the hardness of folding strips depending on load;

– draw conclusions regarding the behavior of the material of folding strips under the influence of various loads, based on the constructed regression model and descriptive statistics;

– recommend optimal loads for the use of folding strips under various conditions.

5. Results of investigating the influence of reinforcing microrelief guides on the efficiency of folding integrated covers

5. 1. Results of research on the improvement of folding strips using microrelief guides formed by a laser beam

The final stage of production of integrated book and journal covers is carried out on the folding and gluing line. At this stage, the covers are moved along the stationary folding strips. Profile folding strips help bend the sweep flaps at an angle that gradually changes from 0° to 180° (Fig. 1). This enables full fit and adhesion of the flaps to the base of the cover sweeps.

Further calendering of the glued integrated covers fixes the geometric orientation of the flaps in the composite structure (chrome ersatz: glue: chrome ersatz). Taking into account the tight tolerances of possible deviations from the rectangular geometry of the covers, the selection of a curvilinear profile of folding strips, materials, and strengthening technologies is important and necessary in the design of folding mechanisms. This makes it possible to ensure high accuracy and quality of book articles as a whole.

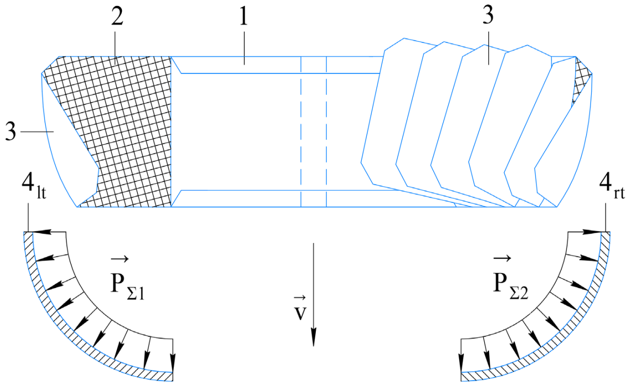


Fig. 1. Stages of folding flaps of integrated covers with profile strips: 1 – glued longitudinal flaps (edges); 2 – adhesive layer; 3 – separate stages of folding transverse flaps; 4_{lt}, 4_{rt} – profile folding strips; $\vec{V}$ – vector of the direction of the sweep speed; $\overline{P_{\Sigma 1}}$, $\overline{P_{\Sigma 2}}$ are the vectors of the distributed pressure forces of the cover flaps on the working surface of strips during folding

When designing profile strips for high-speed folding of covers, it is advisable to use curvilinear contours developed on the basis of mathematical models (Table 1). This ensures optimal smoothness of the technological process and increases the quality of the resulting articles.

Table 1

Selection of curvilinear contours for the design of profile strips

No.	Curved paths	Parameter
1	Involutes	$x(t)=R(\cos t)+t(\sin(t))$, $y(t)=R(\sin t)-t(\cos(t))$, where R – radius of the initial circle, t – curve parameter
2	Bernoulli curves (logarithmic spirals)	$r(\theta)=ae^{b\theta}$, where a and b – constants that determine the shape of the helix, θ – angle
3	Splines (cubic splines)	Building splines requires defining control points and calculating an interpolation curve that ensures a smooth transition between those points
4	Bezier curves	$B(t)=(1-t)^3P_0+3(1-t)^2tP_1+3(1-t)^2P_2+t^3P_3$, where P_0–P_3 – control points, t – curve parameter from 0 to 1

Taking into account the results of research on curvilinear contours [1], it was determined that the use of involute curves to form profile folding strips enables smooth and accurate bending of the flaps of integrated covers. To manufacture folding strips with a profile plane that corresponds to an involute curve, the curve is extruded along the Y axis, perpendicular to its plane (Fig. 2).

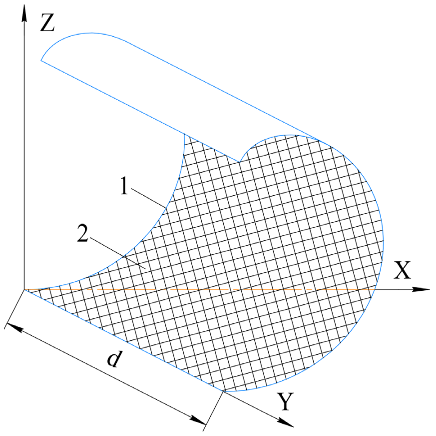


Fig. 2. Fragment of a profile involute folding strip: 1 — a fragment of an involute; 2 — working surface of the strip; *d* is the thickness of the extrusion

The length of the curve L is determined by integrating its arc elements. For the involute of a circle, the length of the curve from the beginning to the point with the parameter t is defined as:

$$L = \int_0^t \sqrt{1+(\theta)^2}\, d\theta, \tag{1}$$

and the surface area of the extrusion as $S = L \cdot d$, where d is the thickness of the extrusion.

Folding strips for integrated cover sweeps are made from flat plates by mechanical forming of the profile. To this end, specially made molds or stamps are used, which are especially effective in mass production. Rolling machines are also used, which allow bending the material of the plate according to the curvilinear contour of the involute. An important aspect is the sequence of the technological process of applying microrelief guides. This can be done both before the formation of the curvilinear profile of the folding strips and after its formation, depending on the requirements for accuracy and preservation of the microrelief.

Applying microrelief after mechanical profile formation, in order to avoid possible damage to fine microstructures, makes it possible to maintain high accuracy and functionality of the working surface of folding strips (Fig. 3). In this regard, it is advisable to use laser technologies for applying a reinforcing microrelief after the mechanical formation of the profile of the folding strips. These technologies ensure high accuracy and minimal impact on the material.

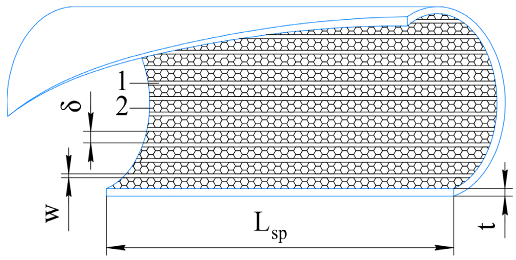


Fig. 3. Fragment of a profile folding strip with a strengthening micro-relief of the working surface and micro-relief guides: 1 — micro-relief guides; 2 — strengthening microrelief; *t* — thickness of folding strip; *w* — width of microrelief guides; Δ is the distance between the guides; L_{sp} — length of the supporting fastening part

A comprehensive mathematical description of the process of modeling the improvement of the working surfaces of the folding strips, processed with a laser beam to form microrelief guides, takes into account changes in surface hardness, friction coefficient, and wear resistance. Microrelief geometry, thermal conductivity, mechanical properties of the cover material, and technological parameters of laser hardening are also taken into account (Table 2).

Table 2

Parameters of improving the working surface of folding strips

No.	Improvement parameter	Units of measurement	Direction of action
1	Surface hardness	(H)	After laser hardening
2	Coefficient of friction	(μ)	Between the bar and the cover material
3	Durability	(W)	Percentage change
4	Geometry of microrelief	(λ, γ)	Height and pitch of guides
5	Thermal conductivity	(κ)	Material strips
6	Mechanical properties of the cover material	(E, ν)	Modulus of elasticity and Poisson's ratio
7	Technological parameters of laser hardening	(P, v, d)	Laser power, scanning speed, beam diameter

Surface hardness after laser hardening is determined from the following formula:

$$H = H_0 + k_1 \cdot \left(\frac{P}{v \cdot d}\right)^{n_1}, \tag{2}$$

where H_0 is the initial surface hardness; k_1 is a coefficient that takes into account the material and properties of the laser; n_1 is an experimentally determined indicator.

The change in the friction coefficient is described as a function of the geometry of the microrelief:

$$\mu = \mu_0 - k_2 \cdot \left(\frac{\lambda}{\gamma}\right)^{n_2}, \tag{3}$$

where μ_0 is the initial coefficient of friction; k_2 – coefficient that takes into account the influence of microrelief; n_2 is an experimentally determined indicator.

The increase in wear resistance can be estimated as:

$$W = W_0 \cdot \left(1 + k_3 \left(\frac{P}{v \cdot d}\right)^{n_3}\right), \tag{4}$$

where W_0 is the initial wear resistance; k_3 is a coefficient that takes into account the material and the laser hardening process; n_3 is an experimentally determined indicator.

The geometry of the microrelief affects the distribution of load and friction. The optimal values can be determined experimentally for the maximum reduction of the coefficient of friction and increase of wear resistance.

Thermal conductivity determines the distribution of heat during folding:

$$\Delta T=\frac{Q}{k\cdot S}, \tag{5}$$

where ΔT is the temperature increase; Q is the amount of heat released due to friction; S is the contact area.

The mechanical properties of the cover material determine the deformation during folding:

$$\sigma=\frac{F}{S}, \tag{6}$$

where σ is tension; F is the force applied to the material; S is the cross-sectional area.

The optimal parameters of laser hardening can be determined experimentally to achieve maximum values of hardness and wear resistance at minimum values of the coefficient of friction for materials of folding strips.

5. 2. Results of determining the optimal parameters for laser strengthening of folding strips

In order to achieve maximum strengthening of the surface of folding strips, the optimal shape of the microrelief should ensure uniform distribution of loads, minimize friction and wear, as well as improve heat dissipation. Taking into account current research and the results from [13], a selection of parameters was formed for the preliminary analysis of the most promising cross-sections of microrelief guides with different geometric parameters (Fig. 4):

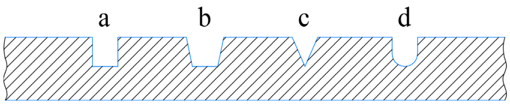


Fig. 4. Geometric parameters of microrelief guide sections: *a* – rectangular; *b* – trapezoidal; *c* – V-shaped; *d* – U-shaped

These parameters depend on the laser settings, the type of processed material, and the specific treatment technology (Table 3):

Table 3

Selection of parameters for cross-section types of microrelief guides formed by a laser beam

No.	Cross-section type of micro-relief guides	Depth (μm)	Width of the top (μm)	Width of the lower part (μm)	Groove spacing (μm)
1	Rectangular	20	50	50	100
2	Trapezoidal	30	50	30	150
3	V-shaped	25	50	0	120
4	U-shaped	20	40	0	80

After analyzing the geometry and cross-section parameters of micro-relief guides, it should be noted that U-shaped cross-sections are the most suitable for strengthening the surfaces of folding strips due to the following advantages. The rounded shape of the U-shaped sections enables an even distribution of the load on the entire surface, which reduces the risk of deformation and increases the overall wear resistance. This, in turn, reduces the friction coefficient between the folding strip and the cover material, improving the accuracy and efficiency of folding.

The rounded shape also promotes better air circulation and heat removal, which reduces the risk of overheating of the folding strips during operation. Due to their shape, the U-shaped micro-relief guides are less likely to accumulate flaked material from the surface of integrated cover sweeps, which helps reduce wear on the surface of the folding strips.

The optimal geometry of U-shaped sections of microrelief guides can be expressed as follows. The profile of the U-shaped guide is represented as a function that depends on the x-coordinate of the cross-section width. The optimal shape can be represented by a parabola or a semicircle. For simplification, a parabolic profile is used:

$$y(x)=\left\{h-\frac{4h}{w^2}\cdot\left(x-\frac{w}{2}\right)^2\right\}, 0\leq x\leq w, \tag{7}$$

where h is the depth of the section; w – cross-section width; x – cross-section width coordinate; $y(x)$ is the height of the section at point x.

The distance between the microrelief guides (Fig. 3) is defined as:

$$p\approx w+\delta, \tag{8}$$

where Δ is the distance between the microrelief guides, which ensures sufficient surface strength.

General formula for a periodic profile:

$$y_{\Sigma}=y\left(x\operatorname{mod}\left(w+\delta\right)\right), \tag{9}$$

where $y(x)$ is the profile of a separate microrelief guide; $y_{\Sigma}(x)$ is a periodic surface profile with microrelief guides; mod – the operation of taking the remainder from division.

Based on the data given in Table 3 for the U-shaped section of microrelief guides:

1. The form of the U-shaped microrelief guide:

$$y(x)=20-\frac{4\cdot 20}{40^2}\cdot(x-20)^2. \tag{10}$$

2. Optimal step:

$$p\approx 40+80=120\,\mu m.$$

3. The general formula for the periodic profile is:

$$y_{\Sigma}(x)=20-\frac{4\cdot 20}{40^2}\cdot(x\operatorname{mod}-20)^2. \tag{11}$$

This mathematical description makes it possible to accurately determine the shape and location of the U-shaped microrelief guides on the working surface of the folding strips (Fig. 3). This provides optimal conditions for reducing friction, improving heat transfer and load distribution.

Taking into account the technological features of folding and gluing of flap flaps, folding strips made of AISI 347 and AISI 1005 steels were chosen for comparative analysis. These grades of steel, used in the manufacture of profile folding strips for integrated book and journal covers, provide an optimal combination of properties for a wide range of applications.

The gluing of the sweep flaps is carried out using polyvinyl acetate dispersions (PVA), which contain a significant amount of dissolved water (40–60 %). During high-speed folding of the flaps, a small amount of PVA gets on the folding strips and causes rusting of the metal of the strips. This, in turn, is an inhibitory factor in the formation of high-quality covers and reduces the wear resistance of the working surface of the strips.

In order to identify the advantages and disadvantages of using AISI 347 and AISI 1005 steel for the manufacture and subsequent production operation of profiled folding strips, the devised procedure for detecting dimensional indicators of wear of the working surface was used. This methodology makes it possible to evaluate in detail the effectiveness and duration of operation of strips made of different types of steel.

Archard's Wear Law [14] was used to predict the wear of materials under sliding conditions and to model the calculation of wear and tear, as well as to further build the calculation model. This law provides a basis for accurately determining wear by considering key parameters such as load, sliding path, and material hardness:

$$V = k \cdot \frac{L \cdot S}{H}, \tag{12}$$

where V is the volume of worn material; k – wear coefficient; L – normal load; S – sliding path; H is the hardness of the material.

The formula for calculating the wear of the working surface of the profile strips, which are used for folding the scans of integrated book and journal covers, takes the following form:

$$V = k \cdot \frac{P \cdot v \cdot t \cdot \mu}{H} \cdot f\left(CR, WS, TC, YM, IV\right), \tag{13}$$

where V is the volume of worn material; k is an empirical coefficient that depends on wear conditions; P – specific pressure; v – friction speed; t – friction time; μ – coefficient of friction; H – hardness; CR – corrosion resistance; WS – wear resistance; TC – thermal conductivity; YM – modulus of elasticity; IV – impact viscosity.

The function $f(CR, WS, TC, YM, IV)$ takes into account the influence of additional properties on the wear of folding strips:

$$f\left(CR, WS, TC, YM, IV\right) = \\ = \frac{\left(1+CR\right)\cdot\left(1+WS\right)\cdot\left(1+TC\right)\cdot\left(1+YM\right)\cdot\left(1+IV\right)}{5}. \tag{14}$$

This function standardizes the additional properties by providing a proportional contribution of each property to the overall wear formula.

Table 4 gives the basic and additional wear parameters of profile folding strips, as well as their dimensional indicators, necessary for modeling and further calculation.

Given these parameters, the calculated wear formula for AISI 1005 and AISI 347 steel takes the following form:

$$V_{1,005.347} = k \cdot \frac{P \cdot v \cdot t \cdot \mu}{H} \times \\ \times \frac{\left(1+CR\right)\cdot\left(1+WS\right)\cdot\left(1+TC\right)\cdot\left(1+YM\right)\cdot\left(1+IV\right)}{5}. \tag{15}$$

Based on our calculations and their results, indicators of the volume of worn material (in conditional units) are listed in Table 5. These values confirm that AISI 347 steel has less wear and higher wear resistance compared to AISI 1005 under the same operating conditions.

Table 4

Basic and additional wear parameters of folding strips

No.	Parameter	Measurement units	AISI 1005	AISI 347
1	Coefficient of friction (μ)	–	≈0.6 metal vs cardboard	≈0.5 metal vs cardboard
2	Specific pressure (P)	MPa	0.5	0.5
3	Friction velocity (v)	m/s	1	1
4	Friction time (t)	hour	100	100
5	Hardness	HB	≈95	≈217
6	Corrosion resistance	point	medium (0.5)	high (1.0)
7	Durability	point	medium (0.5)	high (1.0)
8	Thermal conductivity	W/m·K	51.9 (0.8)	16.3 (0.3)
9	Modulus of elasticity	GPa	205 (0.9)	190 (0.8)
10	Impact strength	J	100–150 (0.8)	50–80 (0.6)

Table 5

Volume of worn material

No.	AISI 1005	AISI 347
1	0.875	0.345

To strengthen the working surface of the profiled folding strips and create an additional guiding effect for the sweeps of integrated covers, it is possible to use the technology of laser formation of micro-relief guides. These guides can be made in the form of a solid continuous line or created by point formation of microrelief with successive bursts of a laser beam.

Solid continuous micro-relief guides (Fig. 3) contribute to the uniform distribution of loads along the entire length of the folding strip, which enables more uniform strengthening. This, in turn, reduces the likelihood of microcracks and defects due to the absence of sharp transitions between treated zones. Thus, integrated microrelief guides contribute to increased wear resistance, as they reduce stress concentration and reduce material wear.

However, continuous exposure to the laser can lead to significant thermal effects, such as thermal deformation or change in the microstructure of the material, which can reduce its mechanical properties. In this regard, more precise control of the laser processing process is needed to ensure a constant depth and width of the microrelief guides. This approach makes it possible to minimize unwanted effects and improve the quality of strengthening.

In turn, spot forming reduces the overall thermal load on the material, as the laser energy is distributed between flashes, which reduces the likelihood of thermal deformation. This method allows for more flexible control of machining parameters such as the depth and width of the micro-relief guides by changing flash parameters. As a result, it is possible to form complex and precise microreliefs owing to the programmable control of laser pulses.

However, variations in the depth and width of the microrelief guides between flashes are possible, which can lead to non-homogeneous strengthening and stress concentrations in the places of transitions. Microcracks and other defects may occur at intersections or overlaps of flashes, especially if the laser parameters are incorrectly set. As a result of the discontinuity of the structure, wear resistance may decrease in the places of transitions between flashes.

Formulas were derived to simulate the calculation of the dependence of changes in mechanical properties and hardness of AISI 347 and AISI 1005 steel samples after laser hardening with the formation of microrelief guides. They will help analyze the differences between solid continuous micro-relief guides and guides formed by point forming.

The thermal effect during laser processing can be estimated through the energy density of the laser beam E:

$$E=\frac{P}{S_i}, \tag{16}$$

where P is the power of the laser beam (W); S_i is the area of influence of the laser beam (m^2).

The thermal effect can be estimated through the temperature change ΔT:

$$\Delta T=\frac{E\cdot\eta}{\rho\cdot c_p\cdot d}, \tag{17}$$

where η is the laser energy absorption coefficient; ρ – material density (kg/m^3); c_p – specific heat capacity (J/kg·K); d – depth of laser exposure (mm).

For point formation, the thermal effect of each flash can be calculated similarly:

$$E_{pnt}=\frac{P\cdot t_p}{S_l}, \tag{18}$$

where t is the time of one flash (s).

Temperature change for one flash:

$$\Delta T_{pnt}=\frac{E_{pnt}\cdot\eta}{\rho\cdot c_p\cdot d}. \tag{19}$$

Total temperature change for N flashes:

$$T_\Sigma=N\cdot\Delta T_{pnt}. \tag{20}$$

Hardness after laser hardening can be estimated through an empirical formula that takes into account the dimensions of the microrelief and the hardening method.

Solid continuous microrelief guide:

$$H=H_0+k+\ln\left(1+\frac{w\cdot d}{S_l}\right), \tag{21}$$

where H_0 – initial hardness (HV or HRC); k – strengthening coefficient, which depends on the method and material; w – guide width (mm); d – guide depth (mm); S_i – area of laser influence (m^2).

The hardness after point formation can be estimated through the sum of the contributions from each flash:

$$H=H_0+k\cdot N\cdot\ln\left(1+\frac{w_{pnt}\cdot d_{pnt}}{S_{pnt}}\right), \tag{22}$$

where N – number of flashes; w_{pnt} – width of one impact point (mm); d_{pnt} – depth of one impact point (mm); S_{pnt} – area of one point of impact (m^2).

Wear resistance can be evaluated through the change in surface hardness. The higher the hardness, the higher the wear resistance.

Solid continuous microrelief guide:

$$W=W_0\cdot\left(\frac{H_\Sigma}{H_0}\right)^n, \tag{23}$$

where W_0 is the initial wear resistance; n is an empirical coefficient that depends on the material.

Point formation (consecutive flashes):

$$W_\Sigma=W_0\cdot\left(\frac{H_\Sigma}{H_0}\right)^n, \tag{24}$$

where H_Σ is the hardness after hardening by point forming.

For production use, the choice of specific parameters depends on the experimental data and operating conditions of profile strips for folding integrated covers.

5. 3. Results of investigating the physical-chemical processes of strengthening and wear resistance of profile folding strips

Laser strengthening of the working surface of folding strips includes several basic physical-chemical processes that lead to a significant improvement in mechanical properties. These processes include absorption of laser energy, heating and melting, rapid cooling, crystallization, and chemical changes on the surface.

When a laser beam hits the surface of AISI 347 steel, it heats up to high temperatures, exceeding the melting point, which is approximately 1400–1420 °C. AISI 347 stainless steel contains chromium and carbon, which can react with the formation of chromium carbides in the area of the laser. Local melting of steel takes place in the zone of laser influence. After the laser stops, the molten material cools down quickly. During cooling, crystallization occurs, forming a fine-grained structure and new phases (Fig. 4, 5), such as chromium carbides, the main of which is chromium carbide $Cr_{23}C_6$:

$$23\mathrm{Cr}+6\mathrm{C}\rightarrow\mathrm{Cr}_{23}\mathrm{C}_6. \tag{25}$$

Chromium from the steel surface and carbon from the molten microrelief zone interact to form different chromium carbides, depending on concentrations and cooling conditions:

$$7\mathrm{Cr}+3\mathrm{C}\rightarrow\mathrm{Cr}_7\mathrm{C}_3, \tag{26}$$

$$4\mathrm{Cr}+\mathrm{C}\rightarrow\mathrm{Cr}_4\mathrm{C}. \tag{27}$$

After cooling and the formation of chromium carbides, these solid phases are evenly distributed over the fine-grained structure of the steel, which significantly increases the hardness and wear resistance of the surface.

Summarizing, the process of formation of chromium carbides in AISI 347 stainless steel during laser hardening can be represented by the following formula:

$$23\mathrm{Cr}+6\mathrm{C}\xrightarrow{\text{laser heating}}\mathrm{Cr}_{23}\mathrm{C}_6, \tag{28}$$

or

$$7\mathrm{Cr}+3\mathrm{C}\xrightarrow{\text{laser heating}}\mathrm{Cr}_7\mathrm{C}_3. \tag{29}$$

Cementite (Fe_3C) is one of the main phases formed during the hardening of carbon steels, such as AISI 1005.

During laser hardening, the formation of cementite occurs in several stages, which include the diffusion of carbon and iron in the high temperature zone.

At a temperature above the eutectoid transformation point (~727 °C), carbon diffuses into austenite (γ-Fe), creating a supersaturated solution:

$$\mathrm{Fe} + \mathrm{C} \xrightarrow{\text{laser heating}}$$
$$\xrightarrow{\text{laser heating}} (\gamma - \mathrm{Fe,C})(\mathrm{supersaturated\_austenite}). \qquad (30)$$

Upon rapid cooling, austenite transforms into martensite (α′-Fe), which contains carbon:

$$(\gamma - \mathrm{Fe,C}) \xrightarrow{\text{fast cooling}} (\alpha' - \mathrm{Fe,C})(\mathrm{martensite}). \qquad (31)$$

In the zone affected by the laser, upon further cooling, martensite is transformed into pearlite or bainite, and carbon reacts with iron, forming cementite (Fe_3C):

$$3(\alpha' - \mathrm{Fe,C}) \xrightarrow{\text{cooling}} \mathrm{Fe_3C}(\mathrm{cementite}). \qquad (32)$$

Cementite forms thin, hard phases in the microstructure of the surface layer of profile folding strips, increasing hardness and wear resistance (Fig. 6, 7).

Table 6 gives the main factors and dimensional indicators of the comparison of physical-chemical processes of improving the mechanical properties of folding strips made of stainless and carbon steel.

Physical-chemical processes during the laser formation of microrelief guides on the surface of folding strips made of stainless steel AISI 347 and carbon steel AISI 1005 differ significantly. AISI 347 stainless steel has a high chromium content, which contributes to the formation of chromium carbides, which increase corrosion resistance and wear resistance. Carbon steel AISI 1005, on the other hand, forms cementite and pearlite, which also increase mechanical properties, but less effectively in terms of corrosion resistance.

These differences in physical-chemical processes affect the characteristics of the surfaces of folding strips after laser treatment. The images below, obtained with the help of a scanning electron microscope (SEM), demonstrate the results of laser strengthening of the surface layer of folding strips. The images (Fig. 5–8) illustrate the surface of AISI 347 stainless steel folding strips with applied microrelief.

The point microrelief on the surface of the folding strip made of stainless steel AISI 347 (Fig. 5, *a*) consists of evenly distributed depressions created by a laser beam. Each point has clearly defined edges and a uniform depth, which indicates the high precision of laser processing and ensures the uniformity of the processed surface. This contributes to the even distribution of mechanical loads.

In Fig. 5, *b*, defects and irregularities are visible on the surface of the point microrelief. Some points show irregularities and microcracks, which can occur due to thermal stresses during laser processing, affecting mechanical strength and wear resistance.

Fig. 5, *c* compares different types of point microrelief on the surface of the folding strip. Dots can have different shapes, sizes and locations depending on laser processing modes. This comparison allows determining the optimal parameters for improving mechanical properties such as wear resistance and hardness.

Spectral analysis (Fig. 6, *a*) reveals that the main component of point microrelief is iron (Fe), which ensures the mechanical properties of the material. Chromium (Cr) increases corrosion resistance and wear resistance due to the formation of carbides. Nickel (Ni) improves plasticity and impact toughness, and oxygen (O) indicates the formation of oxides that affect surface properties.

Fig. 7 shows micro-relief guides on the surface of AISI 347 stainless steel folding strips.

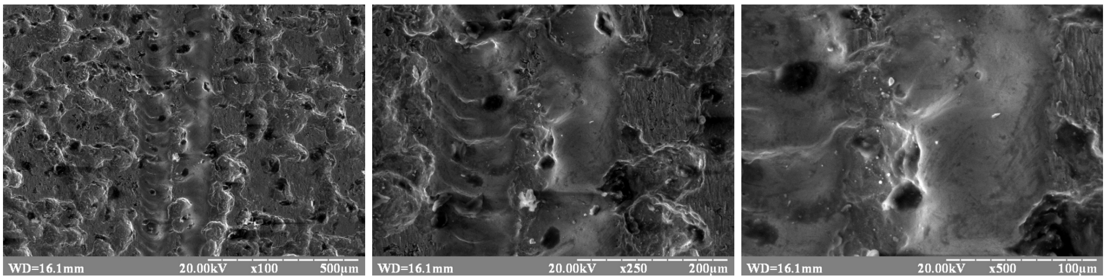
Images and spectral analyzes (Fig. 7, 8) show that the micro-relief guides applied to the surface of AISI 347 stainless steel folding strips have a clear structure and a homogeneous composition. The content of chromium and nickel contributes to the improvement of corrosion resistance, wear resistance, and mechanical properties. However, the presence of defects requires optimization of laser processing parameters to achieve better results.

The images (Fig. 9–12) illustrate the surface of folding strips made of carbon steel AISI 1005 with applied microrelief.

Table 6

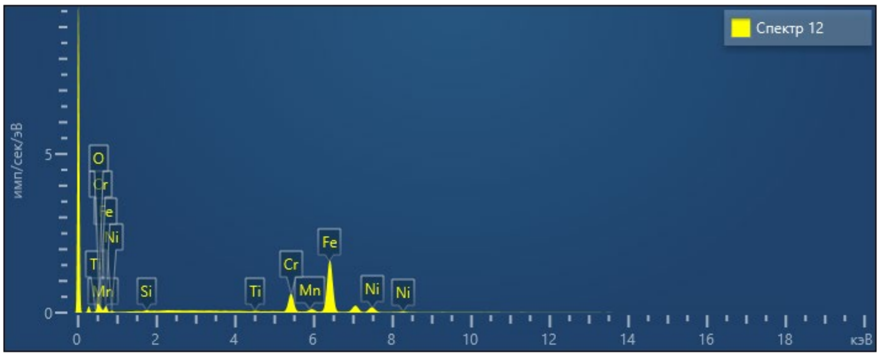
Comparison of physical and chemical processes for improving the mechanical properties of folding strips

No.	Parameter	AISI 347 (stainless steel)	AISI 1005 (carbon steel)
1	Key elements	Chromium (17–20 %), niobium	Iron (>99 %), carbon (to 0.06 %)
2	Melting point	1400–1420 °C	1425–1540 °C
3	Absorption of laser energy	High reflectance	Better energy absorption
4	Cooling and crystallization	Fine-grained structure, chromium carbides	Perlite, bainite, cementite
5	Chemical reactions	$23Cr+6C \rightarrow Cr_{23}C_6$	$3Fe+C \rightarrow Fe_3C$
6	Thermal stability	High, oxidation resistance	Tendency to oxidation



a *b* *c*

Fig. 5. SEM image of a point microrelief on the surface of folding strips made of AISI 347 steel:
a — magnification 100×; *b* — magnification 250×; *c* — magnification 500×

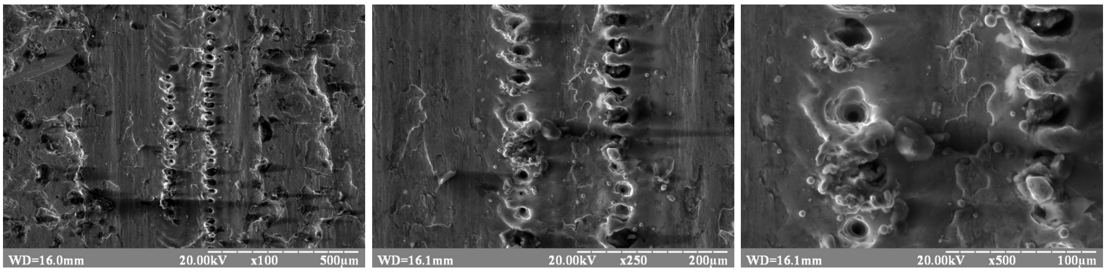


a

Spectrum 12				
Element	**Line style**	**Weight %**	**Sigma weight %**	**Atomic. %**
Ti	K-Series	0.43	0.11	0.40
Cr	K-Series	13.98	0.29	12.01
Mn	K-Series	0.37	0.22	0.30
Fe	K-Series	65.43	0.52	52.34
Ni	K-Series	9.79	0.39	7.45
Si	K-Series	0.34	0.10	0.54
O	K-Series	9.66	0.36	26.96
Total		100.00		100.00

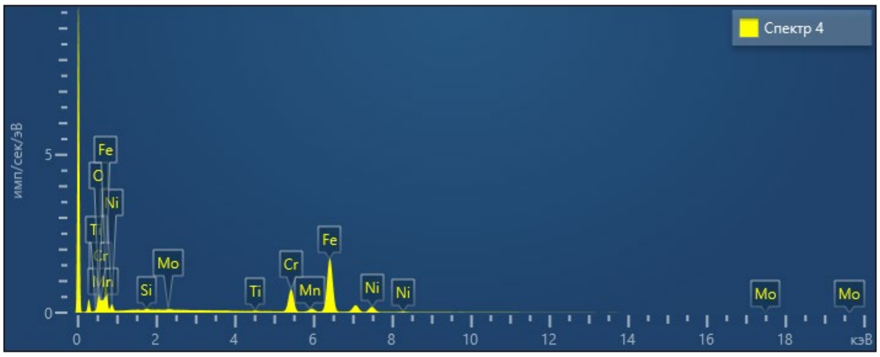
b

Fig. 6. EDS results of the deposition layer on the surface of folding strips made of AISI 347 steel: *a* – chemical composition of the surface after laser treatment; *b* – dimensional indicators of dominant and auxiliary components



a *b* *c*

Fig. 7. SEM image of microrelief guides on the surface of folding strips made of AISI 347 steel: *a* – magnification 100×; *b* – magnification 250×; *c* – magnification 500×



a

Spectrum **4**				
Element	**Line style**	**Weight %**	**Sigma weight %**	**Atomic. %**
Ti	K-Series	0.38	0.09	0.38
Cr	K-Series	16.68	0.27	15.11
Mn	K-Series	0.20	0.18	0.17
Fe	K-Series	64.72	0.48	54.60
Ni	K-Series	10.15	0.33	8.15
Si	K-Series	0.43	0.10	0.72
O	K-Series	7.02	0.34	20.67
Mo	L-Series	0.43	0.26	0.21
Total		100.00		100.00

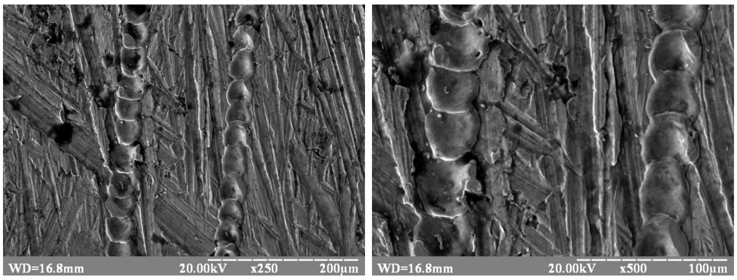
b

Fig. 8. EDS results of the deposition layer on the surface of folding strips made of AISI 347 steel: *a* – chemical composition of the surface after laser treatment; *b* – dimensional indicators of dominant and auxiliary components

The images and spectral analysis show that the microrelief guides (Fig. 9) and point microrelief (Fig. 11) applied to the surface of the folding strips made of carbon steel AISI 1005 have a clear structure and a uniform composition. The iron content is dominant, which provides the main mechanical properties. Defects and irregularities on the surface indicate the need to optimize laser processing parameters to achieve better results.

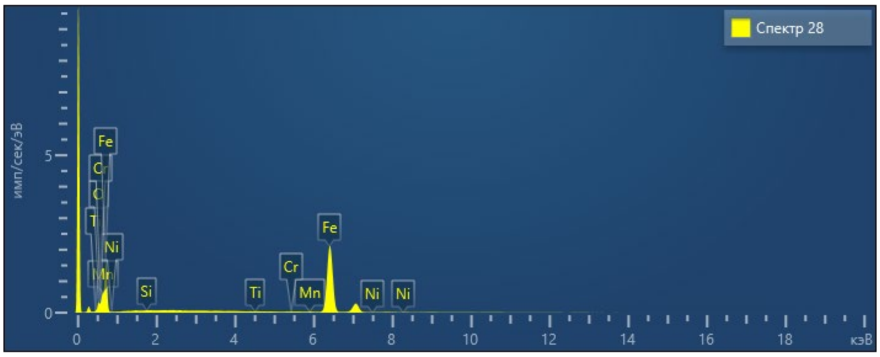
SEM images and EDS results provide information on the microstructure and chemical composition of the surface after laser treatment. However, to confirm the improvement in mechanical properties, hardness measurements must be performed. This will make it possible to evaluate the effectiveness of laser hardening and compare the hardness of different types of steel, determining the optimal material for folding strips. Measurements will also help identify defects, assess their impact on strength and durability, as well as check the uniformity of processing, which will help improve product quality.

Table 7 and plots (Fig. 13) show the results of measuring the hardness of profile folding strips made of stainless steel AISI 347 and carbon steel AISI 1005 after laser strengthening of the surface by applying point microrelief and microrelief guides.



a *b*

Fig. 9. SEM image of microrelief guides on the surface of folding strips made of AISI 1005 steel: *a* — magnification 250×; *b* — magnification 500×

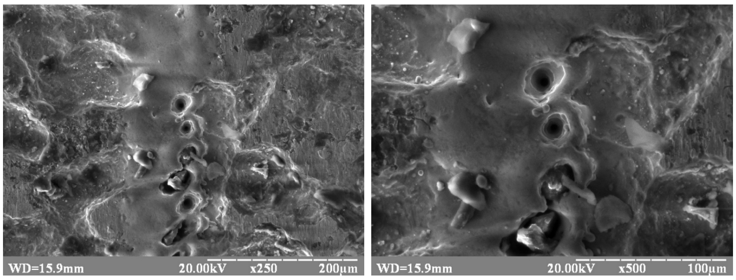


a

Spectrum **28**				
Element	**Line style**	**Weight %**	**Sigma weight %**	**Atomic. %**
Ti	K-Series	0.06	0.14	0.06
Cr	K-Series	0.00	0.14	0.00
Mn	K-Series	0.33	0.20	0.29
Fe	K-Series	93.78	0.61	82.17
Ni	K-Series	0.10	0.28	0.09
Si	K-Series	0.10	0.15	0.18
O	K-Series	5.63	0.48	17.21
Total		100.00		100.00

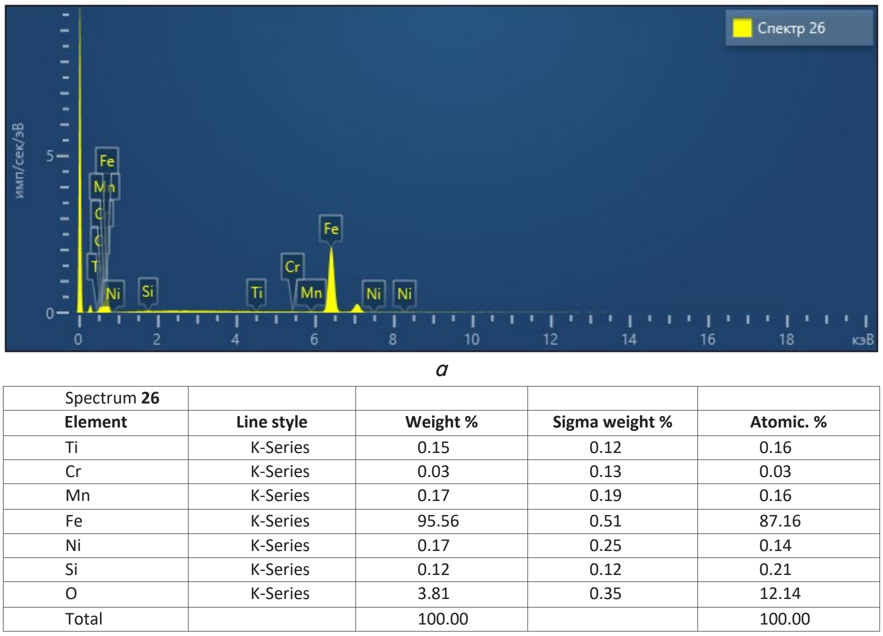
b

Fig. 10. EDS results of the deposition layer on the surface of folding strips made of AISI 1005 steel: *a* — chemical composition of the surface after laser treatment; *b* — dimensional indicators of dominant and auxiliary components



a *b*

Fig. 11. SEM image of point microrelief on the surface of folding strips made of AISI 1005 steel: *a* — magnification 250×; *b* — magnification 500×



a

Spectrum **26**				
Element	**Line style**	**Weight %**	**Sigma weight %**	**Atomic. %**
Ti	K-Series	0.15	0.12	0.16
Cr	K-Series	0.03	0.13	0.03
Mn	K-Series	0.17	0.19	0.16
Fe	K-Series	95.56	0.51	87.16
Ni	K-Series	0.17	0.25	0.14
Si	K-Series	0.12	0.12	0.21
O	K-Series	3.81	0.35	12.14
Total		100.00		100.00

b

Fig. 12. EDS results of the deposition layer on the surface of folding strips made of AISI 1005 steel: *a* – chemical composition of the surface after laser treatment; *b* – dimensional indicators of dominant and auxiliary components

Table 7

A sample of the results from measuring the hardness of folding strips

No.	Load, g	Hardness (strip 1), MPa	Hardness (strip 2), MPa
1	50	4,904	2,141
2	100	4,607	2,086
3	150	4,280	2,035
4	200	3,954	1,983
5	250	3,736	1,892
6	300	3,488	1,766
7	300	3,646	1,786
8	300	3,982	1,778
9	350	3,088	1,665

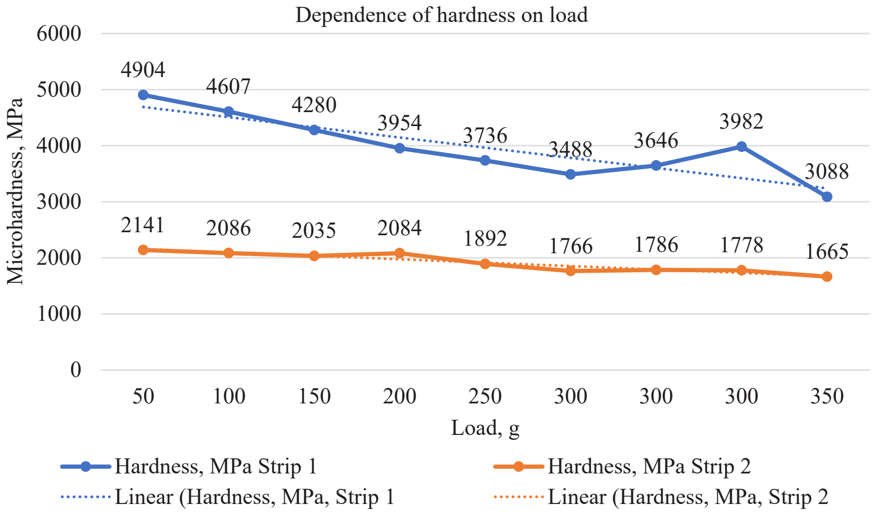


Fig. 13. Plots of dependence of the hardness of folding strips on the load with trend lines

Statistical data processing:

– average load (g):

$$\bar{x}_L = \frac{L_1 + L_2 + L_3 + \ldots + L_n}{n};$$

– hardness (strip 1) MPa:

$$\bar{x}_{H1} = \frac{H_{11} + H_{12} + H_{13} + \ldots + H_{1n}}{n};$$

– hardness (strip 2) MPa:

$$\bar{x}_{H2} = \frac{H_{21} + H_{22} + H_{23} + \ldots + H_{2n}}{n};$$

– standard deviation (σ): load and hardness:

$$\sigma_{L,H_1,H_2} = \sqrt{\frac{\sum (x_i - \bar{x})^2}{n-1}}.$$

For each data column in Table 7, the average value, standard deviation, minimum, maximum, median, and quartiles are calculated (Table 8).

Performing regression analysis and building models.

Calculation of the coefficients of the regression equation:

– slope coefficient (β_1):

$$\beta_1 = \frac{n\sum xy - \sum x \sum y}{n\sum x^2 - \left(\sum x\right)^2};$$

– constant (β_0):

$$\beta_0 = \frac{\sum y - \beta_1 \sum x}{n}.$$

Table 8

Basic elements of descriptive statistics

No.	Parameter	Load, g	Hardness (strip 1), MPa	Hardness (strip 2), MPa
1	Number of observations	9	9	9
2	Average value	222.22	3,965.00	1,903.56
3	Standard deviation	103.41	563.96	165.38
4	Minimum	50	3088	1665
5	25th percentile, (first quartile, Q1)	150	3646	1778
6	50th percentile, (median, Q2)	250	3954	1892
7	75th percentile, (third quartile, Q3)	300	4280	2035
8	Maximum	350	4904	2141

By substituting the experimental data into these formulas, the following results were obtained and listed in Table 9.

Table 9

Coefficients of the regression model for folding strips

No.	Coefficients	Strip 1	Strip 2
1	Slope factor (β_1)	–5.1627	–1.5763
2	Constant (β_0)	5,112.2727	2,253.8442

According to the given values of the coefficients of the regression model of the regression equation:

– for folding strip 1:

$$H_1 = 512.2727 - 5.1627 \times L_1;$$

– for folding strip 2:

$$H_2 = 2,253.8442 - 1.5763 \times L_2.$$

The coefficient of determination (R^2) for folding strips was calculated according to the following formula:

$$R^2_{1,2} = 1 - \frac{\sum \left(H_i - \widehat{H}\right)^2}{\sum \left(H_i - \bar{H}\right)^2}.$$

As a result of calculations, the value of R^2 is 0.896 for folding strip 1 and 0.972 for folding strip 2, which indicates a high level of correspondence of the model to experimental data.

The results of the hardness measurements of the folding strips show that the AISI 347 stainless steel strips (strip 1) have a higher initial hardness compared to the AISI 1005 carbon steel (strip 2). This is confirmed by the measurements shown in Table 6, where the hardness of strip 1 (AISI 347) significantly exceeds the hardness of strip 2 (AISI 1005). The hardness indicators for strip 1 are in the range of 4904–3088 MPa at a load of 50–350 g, with a deviation of 37.1 %. At the same time, strip 2 showed better stability of hardness, which is in the range of 2141–1665 MPa at a load of 50–350 g with a deviation of 22.3 %. This is ensured by the formation of cementite, which also reduces the tendency to plastic deformation. The higher hardness values for AISI 347 indicate greater wear resistance compared to AISI 1005. However, given the reduction in hardness under load, the effect of plastic deformation must be considered in production applications.

Based on our data analysis and regression models, it is recommended to use strip 1 for loads that do not exceed 200 g, due to its high sensitivity to load changes (significant decrease in hardness with increasing load). This will help maintain optimal hardness and ensure the durability of the material. Strip 2, which is less sensitive to load changes, can be used for loads of up to 250 g. This will allow maintaining the necessary hardness and ensure efficient use of the material. If the strips are used under conditions with a constant load, it is recommended to choose strip 2 because it better withstands stable loads. For conditions where the loads change frequently, it is better to use strip 1 for loads up to 150 g to minimize the risk of a significant decrease in hardness. AISI 1005 exhibits greater hardness stability under various loads, which can be an advantage under constant or cyclic loading in service.

6. Discussion of results related to investigating the impact of reinforcing microrelief guides on the efficiency of folding integrated covers

The results of our study showed that an important stage in the production of integrated covers is the folding of flaps with the help of profile strips, which ensures accurate bending without damage to the material. At this stage, the covers are moved along the stationary folding strips. Profile folding strips help bend the sweep flaps at an angle that gradually changes from 0° to 180° (Fig. 1). This ensures complete fit and adhesion of the flaps to the base of the cover sheets, while also helping determine the geometric accuracy of the outer contours and the composite strength of the covers during the folding process.

A study on the influence of reinforcing microrelief guides on the folding efficiency of integrated covers showed that the use of laser microrelief formation significantly improves the mechanical properties of folding strips. A complex mathematical description of the process of modeling the improvement of the working surfaces of folding strips takes into account changes in surface hardness, friction coefficient, and wear resistance. Microrelief geometry, thermal conductivity, mechanical properties of the cover material, and technological parameters of laser hardening are also taken into account (Table 2).

Taking into account the current research and results reported in [13], a selection of parameters was formed for the preliminary analysis of the most promising cross-sections of microrelief guides with different geometric parameters. These parameters depend on the laser settings, the type of processed material, and the specific processing technology (Table 3).

After analyzing the geometry and cross-section parameters of microrelief guides, it was determined that U-shaped guides are the most suitable for strengthening the surfaces of folding strips due to the following advantages. The rounded shape of the U-shaped sections enables an even distribution of the load on the entire surface of the strips, which reduces the risk of deformation and increases the overall wear resistance. This reduces the friction coefficient between the folding strip and the cover material, improving the accuracy and efficiency of folding.

The optimal geometry of U-sections of microrelief guides is expressed as a function of the profile of the U-section, which depends on the x coordinate, using a parabolic or semicircular profile to simplify calculations. The distance between the microrelief guides (Fig. 3) was determined, which provides an optimal step of 120 micrometers and sufficient surface strength.

In order to identify the advantages and disadvantages of using AISI 347 and AISI 1005 steel in the production of profile folding strips, the devised methodology for determining the dimensional indicators of wear of the working surface was used. This procedure makes it possible to evaluate the further production operation of the strips, taking into account their wear resistance and durability. According to the devised methodology, the formulas for calculating the wear of the working surface of the profiled strips have been derived, and the necessary parameters for modeling and further calculations have been established, listed in Table 4. Given these parameters, the estimated wear indicators for carbon steel AISI 1005 are 0.875, and for stainless steel AISI 347 – 0.345, which indicates the higher wear resistance of the latter.

The results of the experiments confirmed the hypothesis of increased hardness and wear resistance of folding strips due to the formation of microrelief guides, which positively affects the quality of the folding process of integrated covers. The results of our study showed a significant increase in hardness and wear resistance of folding strips after laser treatment. This can be explained by the formation of chromium carbides in the case of AISI 347 stainless steel and cementite in the case of AISI 1005 carbon steel. The formation of chromium carbides ($Cr_{23}C_6$) significantly increases the hardness and corrosion resistance of stainless steel, which is confirmed by the results in Fig. 7 and in Table 6. At the same time, the formation of cementite (Fe_3C) in carbon steel ensures significant stability of mechanical properties, which can be seen from Table 4, where the hardness stability indicators of AISI 1005 are higher under various loads.

Unlike methods that focus only on improving hardness or wear resistance, the proposed methodology combines laser processing with the formation of microrelief guides. This makes it possible to simultaneously increase hardness, reduce the coefficient of friction, and improve wear resistance. For example, in work [5], the combined application of laser hardening and ultrasonic shock deformation was reported but the effect of microrelief guides on the folding process was not investigated. The proposed methodology provides more uniform strengthening and reduces the risk of microcrack formation, which is confirmed by the results in Fig. 5.

The obtained solutions make it possible to significantly increase the operational characteristics of the folding strips, which is important for ensuring the high quality of integrated book and journal covers. They enable uniform distribution of mechanical loads, reducing the risk of material damage during folding. This is achieved owing to the optimization of laser hardening parameters, which were determined experimentally and confirmed by the results of measurements shown in Fig. 9–12.

Our research results could be applied to increase the hardness and wear resistance of printing rollers, punching tools, rollers in laminating equipment, as well as tools for punching holes and stapling. This would enable long-term operation, high product quality, and lower maintenance costs.

One of the limitations of this study is possible variations in laser hardening parameters that may affect the results. For example, the non-uniformity of the depth and width of microrelief guides could lead to the concentration of stresses and the formation of microcracks. It is also necessary to take into account possible changes in the properties of materials when changing the technological parameters of processing, which may require additional experiments for optimization.

The disadvantage of the study is that it focuses mainly on the immediate effects of laser microrelief formation on the wear resistance and hardness of folding strips. At the same time, it does not sufficiently take into account the long-term stability of these properties under various environmental conditions, such as humidity, temperature fluctuations, or the aggressiveness of bonding adhesive compositions. In addition, the study mentions a reduction in heat load due to laser treatment. However, no detailed analysis of how different laser parameters (e.g., power, pulse duration) specifically affect thermal effects in the microstructure of materials is presented.

Our research may be advanced through a more detailed study on the influence of different modes of laser processing on the formation of microrelief guides and their influence on the mechanical properties of various types of steel. It is also promising to investigate the effect of combined processing methods, such as laser hardening in combination with other technologies (for example, ultrasonic impact deformation), to further improve the operational characteristics of folding strips.

7. Conclusions

1. A comprehensive analysis and modeling of the process of improving the working surfaces of folding strips processed with a laser beam to form microrelief guides were carried out. The results of our study showed that laser formation of microrelief guides significantly improves the mechanical properties of folding strips. A complex mathematical description of the process takes into account changes in surface hardness, friction coefficient, and wear resistance. The use of laser processing makes it possible to form uniform and precise microrelief structures that enable an even distribution of the load on the surface of the strips, which reduces the risk of deformation and increases the overall wear resistance. The distance between microrelief guides was calculated, which provides an optimal step of 120 µm and sufficient surface strength.

2. The optimal parameters of laser strengthening were determined through experimental studies, which included the analysis of laser power, scanning speed, and beam diameter. According to our research results, the most effective form of microrelief guides turned out to be U-shaped sections. They ensure uniform load distribution, reduce the friction coefficient, and increase wear resistance. According to the devised methodology, the formulas for calculating the wear of the working surface of the profile strips were derived and the necessary parameters for modeling and further calculations were established. Given these parameters, the estimated wear rates for carbon steel AISI 1005 are 0.875, and for stainless steel AISI 347 – 0.345.

3. A comparison of the physicochemical processes of strengthening and wear resistance of profile folding strips made of stainless steel AISI 347 and carbon steel AISI 1005 was performed. The results showed that both materials demonstrate improved mechanical properties after laser hardening. However, AISI 347 proved to be more effective in increasing corrosion resistance and hardness due to the formation of chromium carbides. The hardness indicators for this material are in the range of 4904–3088 MPa at a load of 50–350 g, with a deviation of 37.1 %. At the same time, AISI 1005 showed better stability of hardness, which is in the range of 2141–1665 MPa at a load of 50–350 g with a deviation of 22.3 %. This is ensured by the formation of cementite, which also reduces the tendency to plastic deformation.

Conflicts of interest

The authors declare that they have no conflicts of interest in relation to the current study, including financial, personal, authorship, or any other, that could affect the study, as well as the results reported in this paper.

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Data availability

All data are available, either in numerical or graphical form, in the main text of the manuscript.

Use of artificial intelligence

The authors used artificial intelligence technologies within acceptable limits to provide their own verified data, which is described in the research methodology section.

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