

*This paper reports an analysis of the state of tribological support in the aviation industry. The use of surface strengthening technologies to extend the resource of friction node parts has been prioritized. Modern combined technologies of nitriding and laser treatment of steel surfaces have been reviewed. The mechanism has been elucidated that damages steel 30H2NVFA in the jackscrew actuator of transport aircraft flaps, which occurs due to insufficient surface hardness of the material after a generally accepted heat treatment. Auger electron spectroscopy analysis revealed a high concentration of oxygen on the surface: up to 41.4 at. %; the friction surface carbonation has been detected, especially significant at the surface of the pitting damage. A comprehensive technology of surface strengthening by nitriding+laser selective hardening has been suggested. The radiation power was 1 KW, the diameter of the focus spot was 2.5 mm, and the pitch between the focus spot centers was 2.5 mm. The total area of laser processing was 70 %. The steel temperature exceeded Ac3 and corresponded to the hardening temperature range. The depth of the nitrided layer increased to 400  $\mu\text{m}$ , the maximum hardness on the surface was 1,350–1,380 HV<sub>0.2</sub>. The formation of a solid nitrided layer with a thickness of 200–250  $\mu\text{m}$  was observed, as well as a transition zone composed of column-shaped iron nitrides, which are introduced into the matrix material. As a result, a sharp gradient in the mechanical properties disappears. The tests confirmed that the wear resistance of the comprehensively treated surface was 2.1 times higher under dry friction conditions, and 4.5 times higher when lubricated with the “Era” grease (RF), compared with the 30H2NVFA steel nitrided by the conventional technology. In addition, there was no fragile destruction of the surface; the interaction with oxygen reduced significantly*

*Keywords: tribomechanical systems, friction nodes, nitrided steel, selective laser processing, wear resistance*

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# IMPROVING THE WEAR RESISTANCE OF HEAVY-DUTY ELEMENTS IN TRIBOMECHANICAL SYSTEMS BY A COMBINED LASER-THERMOCHEMICAL PROCESSING METHOD

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## 1. Introduction

With increasing workloads and machines' economic efficiency requirements, increasing their reliability and du-

ability are important. In solving this task, one of the key issues is to ensure a high level of contact strength and wear resistance. Modern machines and vehicles consist of a large number of heavy-duty friction couples. Most of them fail

because of the wear and chipping of contact surfaces. All this makes the improvement of tribological support to such nodes a priority task for materials science and surface engineering.

Examples of such mechanisms are ball screw – ball nut assemblies of flap jackscrew actuator, landing gear kneel mechanisms, horizontal stabilizer positioning mechanism etc. Large flight and ground loads require high strength and elasticity of the material, as well as a high surface strength. Due to vibrations, the strengthened layer's local chipping is observed, especially in the so-called "parking" places of the flaps in the retracted position.

Today, many different surface hardening methods work well under "average" conditions. However, they cannot work effectively in localized (point and line) contacts for many reasons. Some, for example, plasma coatings have low adhesion, "classical" nitriding – a rapid transition of mechanical properties, surface hardening does not provide for the required hardness, etc. [1, 2]. Complex surface engineering technologies have become widely used when 2–3 methods of hardening are performed sequentially [3–6]. This approach eliminates drawbacks and mutually reinforces the advantages of each technique. Thus, plasma spraying followed by laser treatment reduces the coating's brittleness, increases adhesion, hardens the substrate material, and makes it possible to create a smooth transition of mechanical properties [7].

The development of new, highly effective surface hardening methods helps improve mechanical engineering products' competitiveness. The increase of friction surface's service life reduces maintenance and repair expenses. In this regard, research aimed to improve the wear resistance of tribomechanical aircraft systems is particularly relevant [8].

Combined surface engineering methods are based on the consistent or simultaneous use of two or more manufacturing methods of technological influence on the material. Methods that combine the laser treatment with thermomodification saturation, electrospark doping, plasma spraying, etc. are developing quite intensively. Combined methods make it possible to form surface layers with the required mechanical properties and significantly increase the contact strength and wear resistance of components in friction couples [9–18]. Therefore, it is relevant to determine the effectiveness of improving the wear resistance of heavy-loaded parts in tribomechanical systems by a combined laser-thermochemical treatment method.

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## 2. Literature review and problem statement

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Surface engineering methods can solve a wide range of tasks. However, the use of one particular method does not always produce the desired result. In addition, each of them has its drawbacks. New prospects open up with the application of two or more methods simultaneously, the so-called combined or complex technologies. In this case, one strengthening method is primary, the second is auxiliary, which reduces the shortcomings of the first and enhances the strengthening effect.

In the case of a ball-screw mechanism with a complex form of contact, coating methods on the steel surface are ineffective, as far as high pressures between the track and the ball lead to their detachment. Therefore, diffusion surface engineering methods come to the fore. However, they also have a drawback – a small thickness and a high hardness gradient between the strengthened and untreated materials.

To reduce this effect, various techniques are used, for example, a dilute concentration of the saturating element. That increases the thickness of the strengthened surface layer but reduces surface hardness.

For steels, the greatest strength, hardness, and wear resistance are achieved by nitriding. The review of studies [19–28] shows the high efficiency of the combined technology of nitriding+laser processing. This avoids the disadvantages of "classic" nitriding, hardens the material under a nitrided layer, and increases the diffusion layer's thickness.

The authors in [19] carried out pulse-laser treatment of steel surface during nitriding in a gas environment. Such combined processing can provide up to four times the growth of hardness, by 200–400 %. Increasing the concentration of carbon in steel adversely affects its ability to dissolve nitrogen and form hardening chemical compounds; it also decreases the depth of nitrogen diffusion into the material. Iron nitrides and carbonitrides were the main strengthening phases detected. A diode laser was used for a similar purpose: to strengthen the steel AISI P21 (USA) [20]. There was a 40 % increase in surface hardness than untreated material, which is much less compared to previous work [19]. The achieved strengthening effect was due to aluminum (an alloying element of this steel) nitrides formation. In [21], the authors studied the process of laser nitriding using lasers with different wavelengths. They found that the wavelength does not affect the process of steel strengthening and corrosion resistance (different environments were studied) after processing. Increasing the intensity of laser radiation from 1.5 to 3 J/cm<sup>2</sup> leads to an increase in austenite. With a further increase in the intensity of radiation, the amount of austenite decreases. In addition, laser nitriding in ammonium medium was studied [22]. Coating thickness was up to 150 μm with dendrites of iron nitride. Compared to conventional nitriding, there is an increase in hardness by 14 % and wear resistance – twice. Nitrogen replacement with other gases also had a significant effect [23]. Thus, argon is inert and has little impact on the additional hardness: strengthening effect is achieved by quenching the surface. The use of propane provides a hardness of up to 914 HV, compared to the 395 HV achieved after laser hardening in the air. Such ultra-high hardness is due to the decomposition of propane and carbon diffusion into steel. However, the authors did not conduct a study of the hydrogen content on the surface. It was evident that its contents are also high, the steel is probably embrittled, and that technology cannot be used for heavy-duty parts. Interesting technology of nitriding is reported in [4]. Femtosecond laser treatment allows obtaining a nanostructured surface by evaporating part of the material. This technique forms a structure similar to the nanoindentation surface. But, to achieve this result, up to 500 cycles are required at one point; it was obtained only for one steel grade – AISI 304 (USA). However, a frequent drawback of the laser nitriding method is the high temperature of the nitriding process. Together with high-energy radiation, that can lead to local overheating and melting, overhardening of the surface, and the formation of a network of surface cracks [22].

Laser-assisted nitriding of steel with surface melting was studied in [24]. Postmelting makes it possible to get the effect of surface hardening and refining of the structure. The nitrogen concentration in the surface material is 0.6 %. However, a significant hardness

gradient creates the risk of chipping the laser-treated areas. The authors [25] studied the laser deposition of nitrided powder of low-carbon steel AISI 316L (USA) by laser surfacing. They could control nitrogen content by mixing nitrided powder with non-nitrided. However, the increase in nitrogen content in powders leads to a high porosity coating that is not suitable for our conditions. Laser treatment with melting after nitriding in the plasma medium [26] indicates the possibility of obtaining a strengthening effect by refining the microstructure by ultra-rapid cooling of the melt [27]. The thickness of the modified layer reaches 250  $\mu\text{m}$ , which is an acceptable value. However, the nitrided area without melting has a higher strength. Thus, in the molten zone, the substrate material is mixed with the nitrided layer, reducing the hardness of the laser-treated surface. This result is unacceptable. Therefore, the technology of laser processing with melting for heavy-duty parts also cannot be applied.

An alternative, which has shown its efficiency, is the selective laser spot treatment of nitrided steel after nitriding.

### 3. The aim and objectives of the study

The work aims are to study steel 30H2NVFA strengthened by a combined method: thermodiffusion nitriding with the subsequent selective laser processing; to examine its wear resistance in ball-contact fretting-wear conditions in lubricated and dry friction modes. This steel is used to produce ball screw and ball nut casing (ball barrel) of jackscrew actuators. Ball tracks (grooves) are typically nitrided.

To achieve these goals, the following tasks were set:

- to analyze operational damage of jackscrew actuator parts and to find the reason why they appear;
- to perform tribotechnical studies under conditions close to the actual operation of jackscrew actuator aimed to compare wear resistance of samples of steel 30HGSN2A nitrided by standard technology and treated by a combined method, including nitriding followed by selective laser treatment in self-quenching mode.

### 4. Analysis of damage to the parts of a ball-screw mechanism

One of the most loaded and responsible components in modern aircraft is the ball-screw couples of jackscrew actuators. Here, the balls housed in the ball nut roll in the grooves of the ball screw. The normal operation mode: lubricated (with grease) rolling friction. Balls, as intermediate bodies, usually transmit motion from ball screw to ball nut. The aircraft kneeling mechanism is very similar in operation. In regular operation conditions, they wear due to normal mechanical-oxidative mechanism. In case of overloads, the lubricating mode may change to boundary one, resulting in local overheating of ball screw material. Generally, the wear resistance of these elements is relatively high. However, sometimes an intensive wear and surface damage may occur. We describe one such event below.

During a routine inspection of the kneel mechanism jackscrew actuator (front landing gear), the ball track's helical surface was found to have con-

siderable damage in the form of cracks and kind of metal fragments delamination looking like pitting damage (Fig. 1). On cross-sectional specimens of the ball screw, we revealed cracks propagating deep into the subsurface. (Fig. 2). The shape and size of pits point on contact-fatigue.

The development of fatigue failure under rolling friction is typically due to cyclic normal and shear stresses. This condition is fulfilled at lubricant starvation when rolling bodies slide over the surface or perform combined (rolling+sliding) motion. Also, the stresses developing due to the surface layer's plastic deformation assist this process [28]. As a material for landing gear kneel mechanism ball screws the steel 30HGSN2A is used. To increase its wear resistance and strength, it is heat-treated: quenching+tempering. Material hardness should be not less than 45-48 HRC. The low wear resistance in the described case may result from the material surface layer's low strength and hardness.

Fig. 3, 4, and Table 1 present the study results on the concentration distribution of chemical elements on ball race working surface by Auger spectroscopy. The study was carried out on an intact surface, near the edge and at the bottom of the cavity of the pitting damage, and at depths of 250 and 800 nm from the surface.

The analysis of our results reveals the enrichment of the surface layer with oxygen and carbon. The oxygen concentration on the surface near the edge of the pitt is 27.1 at. %, at a depth of 250 nm and 800 nm, respectively, 41.4 at. % and 29.2 at. %. At the surface of the middle part of the pit, at a depth of 250 nm and 800 nm below the surface, the oxygen concentration is 7.9 %, 18.3 at. %, and 24.0 at. %.

This indicates the intensive interaction of the metal with oxygen, which is likely the result of the development of plastic deformation of surface layers and the effect of elevated temperatures in the contact zone. As mentioned above, this is possible in case of lubricant starvation, also allowing free oxygen inflow to the surface. Maximum carbon content is observed in the pitting damage cavity. The shape of the carbon spectrum line and its concentration indicate the presence of a graphitized film in the cavity.

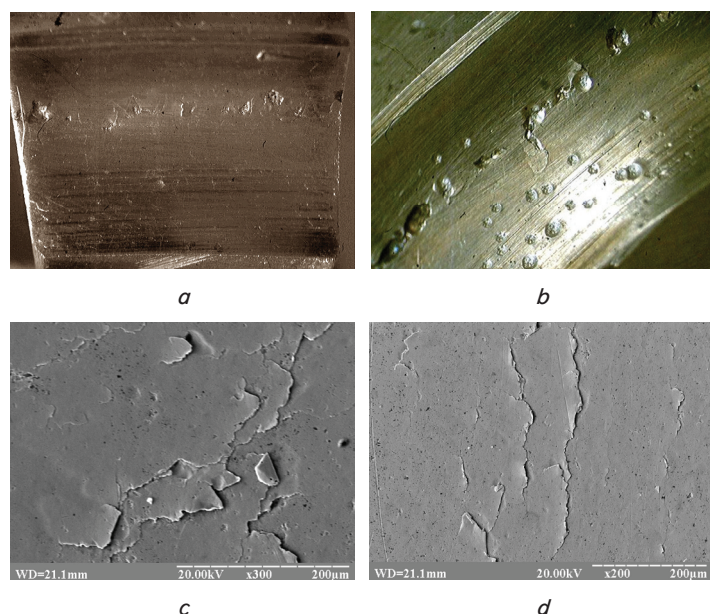


Fig. 1. The damaged surface of ball screw of flaps jackscrew actuator: *a, b* – appearance ( $\times 8$ ); *c, d* – micrograph of damaged regions

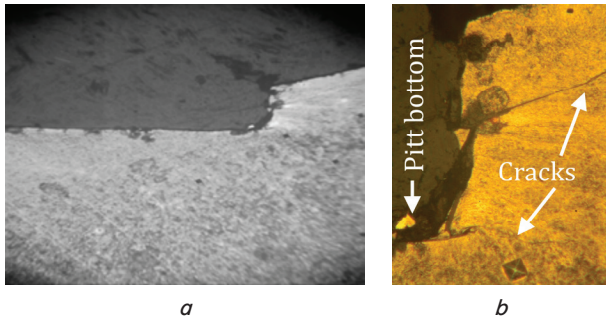


Fig. 2. Micrographs (cross-section) of pitted surface and pitted bottom topography: *a* –  $\times 100$ ; *b* –  $\times 400$

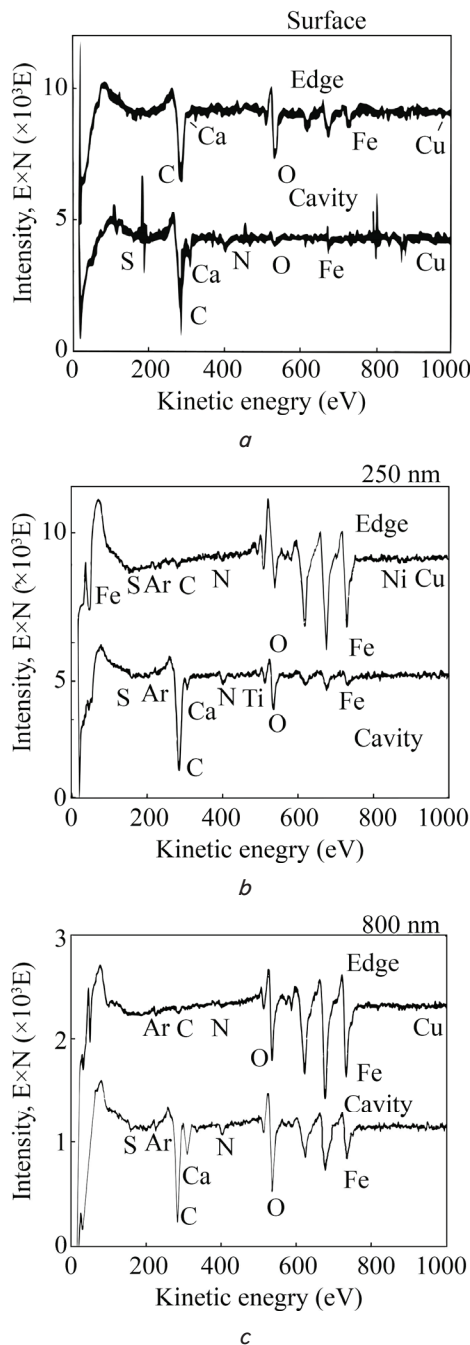


Fig. 3. Auger spectra on jackscrew ballrace surface: *a* – surface; *b* – at a depth of 250 nm; *c* – at a depth of 800 nm

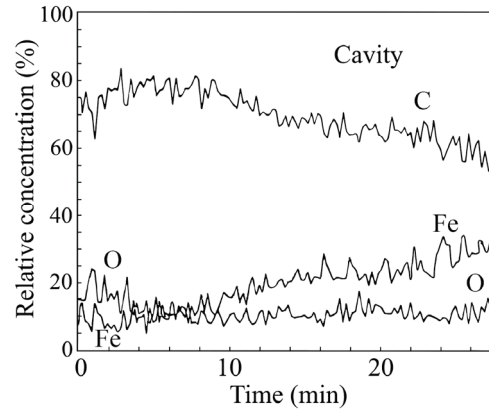


Fig. 4. Auger spectra in depth at the bottom of jackscrew ballrace pitted

Table 1

Elemental composition of micro plots at the working surface of a ballscrew

Depth, Nm	Element concentration, at. %									
	Fe	Ni	Cu	Ti	Ca	C	N	O	S	F
Non-damaged surface										
0	18.8	0.7	–	–	0.9	48.1	2.5	29.0	–	–
Near-cavity surface (edge)										
0	13.1	–	1.9	3.9	0.6	53.4	–	27.1	–	–
250	51.7	1.4	0.9	–	–	2.3	1.7	41.4	0.6	–
800	66.4	–	0.8	–	–	2.1	1.5	29.2	–	–
Cavity bottom surface (point 1)										
0	–	–	–	–	3.3	55.4	10.4	6.0	–	24.9
Cavity bottom surface (point 2)										
0	–	–	1.9	–	1.6	75.2	6.8	7.9	1.9	4.7
250	8.8	–	–	1.2	1.0	64.3	5.6	18.3	0.8	–
800	23.5	–	–	–	2.4	45.3	3.0	24.6	1.2	–

The formation of graphitized surface films in the contact zones during friction was identified earlier [29, 30]. The most likely source of carbon supply to interact with metal is, in this case, carbon, which can be formed as a result of the tribomechanical and thermal destruction of a lubricant. This assumption is proved by high content of sulfur and phosphorus along with carbon. Under the layer of the graphitized film, there are iron oxides. The process of iron oxidation is accompanied by a significant increase in the volume of the material [31]. The formation of oxide phases makes an additional wedging effect on the fatigue crack walls and accelerates the contact-fatigue wear.

When inspecting ball screw and ball nut assembly of flaps jackscrew actuator after 10,000 flight hours of operation, we identified fretting corrosion damage in the form of discoloration, ball-caused brinelling, metal chipping [32–36].

The ball screw-ball nut assembly is made of 30H2NVFA steel, heat-treated to a strength of  $\sigma_u=1,000-1,200$  MPa and nitrided to a depth of 0.2  $\mu\text{m}$  to ensure wear resistance. The maximum damage area is in place (contact of ball screw and ball nut) when flaps are in the “cruising flight” position, and the intermediate flaps position usual for aircraft during maintenance. Due to localized contact and no nut motion along the screw, grease is squeezed out, and a metal-to-metal touch with free oxygen inflow occurs. Very favorable conditions fretting wear appear. The maximum depth of pits at such areas reaches 0.7 mm, which significantly exceeds the depth of the nitrided layer. Similar damage may arise

on the kneel mechanism jackscrew actuator. Therefore, the strength of quenched+tempered and nitrided steels used for ball screw applications is insufficient.

Consequently, the results of our analysis indicate that the level of surface strength and wear resistance of working surfaces of BSM screws, which is achieved both by hardening through heat treatment and nitriding, is insufficient. In both cases, to increase the wear resistance of the working surfaces and high hardness of BSM screws, it is necessary to increase the resistance of the surface layer material against corrosion fatigue. In this regard, nitrided layers on steels cannot provide reliable protection of friction surface under high contact loads due to the relatively small thickness and brittleness.

### 5. Results of studying the wear resistance of comprehensively treated steel 30H2NVFA under fretting conditions

One of the most appropriate ways to solve this problem is to create macroheterogeneous surface layer. More strong areas or spots capable of bearing increased contact loads are embedded in the softer and more ductile matrix material in this type of structure. A monolayer of a “particle-reinforced composite” is formed. Such structures have good bearing and relaxation capacity [32–34]. Macroheterogeneous layer can be formed by the following method: nitriding followed by selective laser treatment in the mode of surface quenching or by combined methods of thermochemical processing [37–41].

Fig. 5 compares the results of fretting-wear tests (in terms of wear intensity) of steel 30H2NVFA samples. Part of the samples was continuously nitrided, and the other one was selectively treated by laser after nitriding (nitriding mode was the same as for first group specimens).

Selective laser treatment was performed according to predetermined spot pattern [42] in the following modes: radiation power: 1 kW, diameter of laser focusing spot: 2.5 mm, the distance between spots: 2.5 mm (the same for longitudinal and transverse directions). This laser treatment mode heats the steel surface to above Ac3 point: quenching temperature. The significant thickness of ball screw material provides fast cooling of thin laser-affected surface layer, and no liquid is required. According to the accepted scheme and geometric parameters of processing, the ratio of specimen area exposed to laser radiation was 70 %.

Wear tests were carried out using ball-on-disc test system under conditions close to the actual BSM working conditions. To get ball-plain contact, the counterpart was designed as a holder with rigidly fixed three balls (diameter of 6 mm, bearing steel ShH-15). The holder with the balls contacts with the sample’s end surface, forming a three-point contact. The test conditions are illustrated in Fig. 5. Since the wear resistance of steel after the nitriding+laser processing turned out to be quite high, it was decided, for this case, to increase the test base to a million cycles. To compare the results, we determined the wear intensity according to the following known formula:

$$J = \frac{h}{2AN},$$

where  $J$  is the wear intensity, dimensionless value;  $h$  is the average linear wear,  $\mu\text{m}$ ;  $A$  is the amplitude of

movement during fretting (moving the sample in one cycle is equal to a double amplitude);  $N$  is the number of fretting cycles).

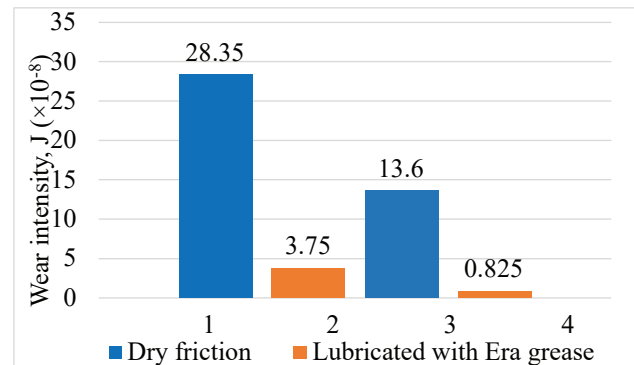


Fig. 5. Wear intensity under fretting conditions: 1, 2 – steel 30H2NVFA+nitriding; 3, 4 – steel 30H2NVFA+nitriding+selective laser processing. Load conditions:  $A=200 \mu\text{m}$ ;  $P_n=980 \text{ N}$ ;  $v=30 \text{ Hz}$ . Test base: 1, 2, 3 –  $N=3 \times 10^5$  cycles; 4 –  $N=1 \times 10^7$  cycles

The test results prove that under both dry and lubricated friction, the samples selectively treated by laser have significantly higher wear resistance than specimens nitrided by standard technology. In dry friction steel 30H2NVFA has a 2.1-time higher wear resistance, and under the conditions of greasing with Era – 4.5 times.

Fig. 6 shows the topography of samples of the nitrided steel 30H2NVFA (a) and the steel processed according to the nitriding+selective LT method (b) after testing for fretting without lubricating. The samples strengthened by nitriding show in the fretting zone the chips and signs of intensive oxidation with the formation of oxide structures characteristic of red-brown iron oxides. The surface of the samples subjected to combined strengthening shows no chips in the fretting zone.

The surface-hardened layer formed by selective laser treatment of pre-nitrided steel consists of two layers (Fig. 7). The outer solid nitride layer is ~ 220  $\mu\text{m}$  thick, the microhardness gradient is 1,350 to 1,180  $\text{HV}_{0.2}$ . Below is the first transition layer with a depth of 220–420  $\mu\text{m}$  from the surface with a microhardness gradient of 1,180–400  $\text{HV}_{0.2}$ . The second transition layer is at depths of 420–600  $\mu\text{m}$  with a hardness gradient of 400 to 360  $\text{HV}_{0.2}$ . It has a columnar structure: inclusions of nitride phase embedded in a relatively soft steel substrate. As one may see, these columns “anchor” the solid nitride layer, and the subsurface fatigue, as we suppose, is majorly arrested.

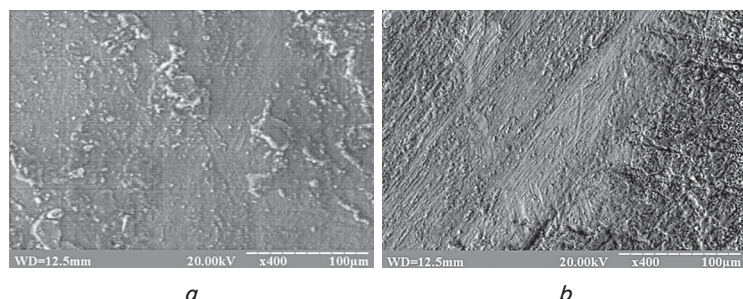


Fig. 6. Topography of samples after fretting wear test, plane-ball contact: a – steel 30H2NVFA, nitriding; b – steel 2HNVFA nitrided+selective laser treatment. Test conditions:  $A=200 \mu\text{m}$ ;  $P_n=980 \text{ H}$ ;  $v=30 \text{ Hz}$ . Test duration  $N=3 \cdot 10^5$  cycles

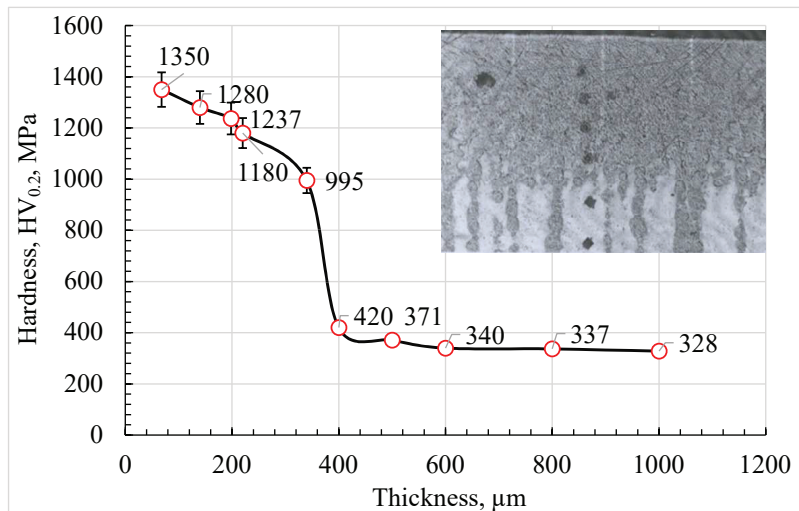


Fig. 7. Microstructure and micro-hardness profile in the surface layer of steel 30H2NVFA after the combined nitriding+selective laser treatment

## 6. Discussion of results of studying the improved wear resistance of heavy-loaded parts in tribomechanical systems by a combined laser-thermochemical treatment

According to the results of our analysis, damage to working surfaces of such heavily loaded parts as the ball screws in flap actuator and landing gear kneel mechanisms is associated with the development of contact fatigue and fretting corrosion. They develop under similar conditions. The level of surface strength and wear resistance of the working surfaces of ball screws, which is achieved today by heat treatment and thermodiffusion nitriding, is insufficient. Thus, nitriding even under the conditions of high contact loads does not provide reliable protection of the steel 30H2NVFA surface from wear. The most likely cause of this is the small thickness of the strengthened layer, increased fragility of the adhesion layer, the high gradient of mechanical properties deep into the surface.

It became possible to avoid the disadvantages of “classical” nitriding and significantly increase steel parts’ wear resistance using combined surface processing: nitriding+selective laser point treatment. As may be seen from Fig. 5, nitrided 30H2NVFA steel samples subjected to selective laser treatment in the quenching mode have 2.1 and 4.5 times more excellent wear resistance compared to nitriding by standard technology in dry and lubricated mode, respectively. The combined technologies involving high-energy laser radiation have made it possible in recent years to devise new effective methods of surface treatment. Due to changes in the structure and strain of surface layers, such methods can change their properties significantly.

According to the data reported in work [35], pulse laser processing, as well as other high-energy pulse-deformation methods of surface metal processing, leads to an increase in dislocations density, acceleration of diffusion processes

in surface layers, redistribution of alloying elements and impurities in the matrix, refining the structure of the material. This process increases the hardness of the surface layer, toughness, corrosion resistance, wear resistance. Besides, under the accepted technological modes of laser treatment of pre-nitrided steel surface, a specific two-layer coating structure is formed (Fig. 7). The upper solid nitride layer provides superior wear resistance. The lower layer’s heterogeneous structure consists of solid columnar inclusions of the nitride phase and ductile sections of the matrix material. This structure contributes to the redistribution and relaxation of stresses from contact loads. Crack growth slows, and the surface’s bearing capacity increases [33, 34]. In contrast to conventional nitriding, it is evident that such a structure can provide higher contact strength and wear resistance under conditions of high contact loads.

In [43], mechanical-pulse processing improved the tribological properties of 30H2NVFA steel by only 15%. It is also proposed to replace the steel 30H2NVFA with VKS-170 (RF) to manufacture the ball screw. However, even in this case, the wear resistance of the pair is twice the wear resistance of the material used today. In [32], the authors also analyzed maintenance peculiarities of the jackscrew actuator of the An-124 aircraft made of 30H2NVFA steel. They only propose to restore the lubricating layer in time. The combined surface treatment technology we suggest here increases fretting resistance twice for dry friction and by 4.5 times for lubricated friction (Era grease as a lubricant).

Therefore, the developed combined technology of surface treatment provides superior wear resistance compared to known analogs and not requires substitution by other material. Since the real friction couple is the contact of two curved surfaces (a sphere in a spherical groove) and not a ball-plane, as in this study, the actual contact area at the same load will be larger, and the contact stresses and wear intensity – smaller.

## 7. Conclusions

1. The technological processes of strengthening ball screws by heat treatment and nitriding (standard technologies) do not provide a high enough wear resistance level under conditions of high local contact loadings.

2. We experimentally proved that an effective way to increase the contact-fatigue strength and fretting-wear resistance of nitrided layers on steel is their subsequent selective laser treatment under the mode of surface self-quenching. After such a combined treatment, the wear resistance of steel increased by 2.1 times in dry friction and by 4.5 times in lubrication (grease Era) compared to nitriding by standard technology.

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