

Розглянуто сумісний вплив попереднього холодного пластичного деформування і екологічних мастильних речовин рослинного походження на поліпшення оброблюваності аустенітних сталей. Це розширює застосування таких сталей як конструкційного матеріалу у машинобудуванні. Досліджено також вплив мікро- та макрорельєфів оброблюваних деталей як технологічного та експлуатаційного факторів. Перший з них полягає у поділі припуску при обробці глибоких отворів, а другий – у поліпшенні експлуатаційних характеристик поверхні деталі. Вивчено вплив плівкових покриттів на підвищення довговічності підшипників кочення. Зокрема, встановлено, що такі покриття заліковують мікротріщини від шліфування обойм та тіл кочення і підвищують надійність цих відповідальних деталей підняттям рівня мікротвердості. Показано, що кривизну твірної глибоких отворів слід зменшувати шляхом зміни напрямків головних рухів на суміжних операціях. Установлено, що на спадковість у механічній обробці треба звертати особливу увагу.

Обґрунтовані шляхи поліпшення оброблюваності аустенітних сталей. Це використання попереднього холодного пластичного деформування для виконання частини роботи різання і переведення парамагнітного стану сталей у магнітний. Також, це застосування при різанні екологічно чистих мастил рослинного походження. Установлено подвійне призначення рельєфів поверхні деталі – технологічне та експлуатаційне. Перше з них виконується спеціальним протяжним інструментом і ефективно при обробці глибоких отворів. Друге призначення полягає у створенні лабіринтів для мастила і поділу оболонки на окремі елементи. Вивчено механізм дії вакуумних плівкових покриттів на надійність підшипників кочення, що полягає у залікуванні мікротріщин від попередньої абразивної обробки і підвищенні твердості поверхні. Показано, що зменшення висоти кривизни глибокого отвору досягається зміною головного руху суміжних операцій.

Результати дослідження є основою для створення технологій відповідальних деталей машин у виробництві

Ключові слова: експлуатаційні властивості, підшипники кочення, аустенітні сталі, регулярні рельєфи, глибокі отвори

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INFLUENCE OF A MATERIAL AND THE TECHNOLOGICAL FACTORS ON IMPROVEMENT OF OPERATING PROPERTIES OF MACHINE PARTS BY RELIEFS AND FILM COATINGS

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1. Introduction

Reliability is the property of an object (a machine, unit, mechanism, and a part) to store in time within the set limits

the values of all parameters that characterize the capability to perform the required functions in the set modes and under conditions of application, storage and transportation [1–3]. Reliability is a comprehensive operational property and

includes failure-free work, durability, maintainability and preservation.

As it is known from the publications relating to engineering of the surface of machine parts, operational properties are determined by 80 % by the properties of the surface of these parts [2]. These properties, in turn, depend on the geometrical parameters, physical-mechanical and physical characteristics of the surface layer of material. Geometric parameters are characterized by macrogeometry, waviness, roughness and direction of part machining trace (heredity). That is why it is advisable to explore mainly waviness and heredity, because other geometric parameters are well-researched.

2. Literature review and problem statement

Source [1] provides a general definition of reliability of technical equipment. However, it is not specified how the reliability of the equipment is ensured by the operational properties of materials, specifically, geometric and physical and mechanical characteristics of surfaces. It is noted in literary source [2] that it is necessary to apply cold plastic deformation to improve machinability of steels by cutting. However, the authors do not present the information about the mechanism of action of such deformation on metal, in particular, nothing is said about the structural transformations of the latter. The role of the surface relief of parts is described only in a fragmentary form. Paper [3] contains the general information about the structure of metallic materials, however, this characteristic is not specified for austenitic steels. Thus, there is no possibility to determine the ways of increasing machinability of such steels by cutting. In the fundamental study [4] on mechanics of cutting process, there is no description of the relationship between the phenomena in the chip formation area and in the contact area on the front surface of a tool. Accordingly, it is not possible to determine machinability criteria from this paper. It does not follow from paper [5] that the most typical indicators of machinability of steels is chip shrinkage and contact characteristics at low and medium rates of cutting. Publication [6] is dedicated to macro structure and its fragments in complex materials, however, its impact on operational, in particular, physical and mechanical properties of surfaces is not considered. Paper [7] tackles these important properties of surfaces of parts, including hardness, elasticity module, etc. It contains the procedure of their research, but there is no information as for the impact of physical and mechanical properties on reliability of machine parts. Publication [8] presents the general characteristics of innovative technologies of compositional strengthening of a surface. However, the application of these technologies to the surfaces with reliefs, rolling bearings, deep openings of tubular parts is not specified. Paper [9], which is also classical, described the PVD method, that is, obtaining vacuum coatings. However, the authors do not cite specific information concerning the application of the method for film vacuum coatings that enhance the reliability of mass parts, in particular, rolling bearings. It is noted in publication [10] that such coatings must be created based on titanium, aluminum and nitrogen, i.e., nitrides. However, this should be considered too narrow for the method. Research [11] is dedicated to surface micro topography, but nothing in it is said about other characteristics of these surfaces. In publication [12], which is dedicated

to the technology of hollow cylinders, there are no data on the methods of dealing with the curvature of generatrix and waviness of the latter.

Thus, the analysis of literature reveals that physical-mechanical and physical properties of the surface layer (micro-hardness, microstructure and texture, dislocations, interaction with lubricants, residual stresses, regular macro- and microreliefs, ferro- and paramagnetism, etc.) have not been sufficiently researched. For this reason, such attention should be paid to the class of paramagnetic austenitic steels as construction material and the material of protective coatings. Characterized by a number of positive properties (wear, corrosion and heat resistance), these steels have extremely low machinability by cutting. The analysis of the literature shows that technological and operational regular micro- and macroreliefs have not been studied enough. The influence of separate not sufficiently studied technological factors and material of parts on the operational properties of the latter should be traced on the example of such mass products as rolling bearings and hydrocylinder sleeves. These sleeves have so-called deep openings, characteristic for the mass class of other parts (shaft hydraulic props, immersion pumps and electric motors, combustion chambers of uncontrolled solid fuel rocket projectiles, various shock absorbers, etc). The technological application of modern film coating of the thickness of 1–5 micron and smaller needs to be studied.

It follows from the above that there is the need for comprehensive research into the influence of material and technological factors on the improvement of operational properties of machine parts.

3. The aim and objectives of the study

The aim of this study is to develop techniques to improve the machinability of austenitic steels and enhancement of the operational properties of a surface of machine parts by creating regular surface reliefs and using protective film coatings.

To achieve the set aim, the following tasks were performed:

- to explore the impact of the preliminary cold plastic deformation and to determine the optimal brand of environmentally friendly lubricating liquid of vegetable origin, which as a result of joint actions would improve machinability of austenitic steels as construction material;
- to develop the methods for obtaining regular micro- and macroreliefs of the surface of machine parts and to identify the areas of technological and operational purpose of reliefs;
- to explore the role and the mechanism of the action of protective film coatings of rolling rings and bodies of rolling bearings from the standpoint of improvement of the reliability of the latter;
- to determine the technological methods for reducing waviness of the surface of deep openings of hollow tubular parts on the example of hydrocylinder sleeves.

4. Results of research into the influence of material and technologies on the operational properties of parts

4.1. Research into the influence of a material

Steels of the austenitic class (heat, corrosion and wear resistant) have exceptionally low machinability by cutting.

This limits the application of such steels in precise machine parts. Most products from austenitic steels are used in engineering without finishing machining. With the purpose of extension of the nomenclature of parts, we carried out the comprehensive study, the result of which was the improvement of machinability of austenitic steel by cutting.

The classics of the science about the mechanics of cutting metals [4, 5] showed that coefficient of chip shrinkage ξ and the length of the full contact of chips with the front surface of the instrument c can reliably testify to machinability of certain metal. A decrease in these indicators would clearly mean machinability improvement.

Based on these conditions and taking into consideration the results of original research [2], it was found that in the area of low and medium cutting rates that are characteristic for machining by a complex tool from fast cutting steel (broaching, threading, grooving, etc.), the factors of the strong influence on machinability of austenitic steels is pre-treatment the latter by cold plastic deformation and the introduction of lubricating-cooling liquids into the cutting area. Cutting rate has a somewhat weaker effect on the process, while other factors, including the front angle, almost do not affect machinability in the range of the studied factors.

The role of preliminary cold plastic deformation is that a part of the work, which would otherwise be done by machining austenitic steel by cutting, is done during the process. In addition, a part of austenite under the influence of deformation is transformed into martensite. That is, steel gets some ferromagnetic properties, which also improves its machinability. The use of the medium of vegetable origin improves contact processes on the front surface of the tool. Thus, as a result we get a double positive effect: from the zone of chip formation through preliminary volume cold plastic deformation, and from the contact zone – through effective environmentally friendly plant medium.

In the process of research, we applied the proposed new effective, but simple method of transversal compression of the machined material, which provided the necessary quantity of this material for experiments. The magnitude of the previous cold deformation was regulated in broad ranges. It was enough to apply a hydraulic press with the force of 20 MPa to do it.

A series of experiments to determine the influence of volume CPD on dislocation density in austenitic steels was conducted. The metallographic sections from steels that were strengthened by deformation and these steels in the non-strengthened state were made at plant Beta Grinder-Polisher of Buehler company. The sections were polished by diamond pastes from synthetic diamonds AM of 60/40 and AFM granularity and ASM of 1/0 granularity. Then the relief with the place of dislocations outlets on the surface was obtained on the surface of section with the use of vacuum etching at the temperature of 920–950 °C. This method makes it possible to study the dislocation structure of austenitic steels. Electronic microscopy ($\times 10,000$) with the help of the microscope REM-106I was applied.

Fig. 1 shows the distribution of dislocations in depth of the samples from steel 08Kh18N10 (AISI 304) in the initial condition (Fig. 1, *a*) and after treatment of CPD (Fig. 1, *b, c*).

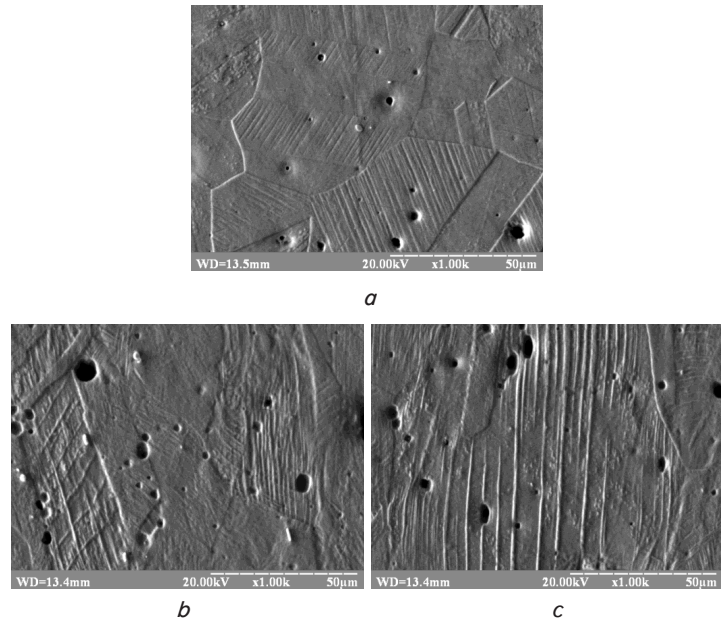


Fig. 1. Distribution of dislocations (large dark pits are the outlet of dislocations on the micro section plane) of the sample from austenitic steel 08H18N10: *a* – in the initial state; *b, c* – after volume CPD

Experiments showed (Table 1) that austenitic steel 08Kh18N10, that is, the doping system (Fe–Cr–Ni) tends to accept plastic deformation most of all. The system (Fe–Cr–Ni–Mn) somewhat decreases this tendency. When it comes to pre-hardened steel 110G13L (Fe–Mn doping system), the action of cold plastic deformation is negligible. This is proved by microphotographs that clearly show the sliding twins, stripes and packs of sliding. The intensity of the latter convincingly shows a different tendency to accept cold plastic deformation by austenitic steels of various doping schemes.

Treatment of microsections with the use of the known techniques showed that dislocation density ρ as a result of processing the samples by volume CPD increases approximately by 4 times.

The accumulation of dislocations serves as the basis for formation of micro-cracks in the material, which improves machinability by cutting austenitic steel.

A series of experiments was conducted to determine the influence of lubricating-cooling liquids on the process of free orthogonal cutting steels of 12H15G9ND, 08H18N10 and 110 G13L brands by the cutter from R6M5 steel with the front angle $\gamma=15^\circ$ and the rate of 0.2 m/s with the cut thickness of 0.03 mm. To do this, we used the stands based of the cross-planing machine of 7M37 model and the horizontal milling machine of 6M83G model and lubricating and cooling liquids – sulphofrezol P and three kinds of oils (sunflower, flax and rapeseed oils). For comparison, cutting was also carried out without lubricating liquids. Preliminary cold plastic deformation was performed using the method of volume compression.

Results of the experiments are given in Table 1.

Analysis of the results of the experiments reveals that all kinds of oils give approximately the same results for improvement of machinability of austenitic steels. That is why, guided by the cost of oils, we choose the cheapest – rapeseed oil.

Comparison of this oil with sulphofrezol P that is most common for cutting processes gave the following results. A joint effect of cold plastic deformation and the medium during cutting austenitic steel 12H15G9ND reduces

coefficient of chips shrinkage by 25 %, and coefficient of contact full length – by 34 %. During machining austenitic steel 08H18N10, these indicators are respectively the following: ξ decreased by 24 %, and c decreased by 34 %. Treatment of wear resistant austenitic steel 110G13L is characterized by the following results: coefficient of chips shrinkage decreased by 16 %, and coefficient of contact full length – by 22 %.

Thus, preliminary cold plastic deformation that was joint with the use of plant-based lubricating-cooling liquids is a powerful means of improving machinability of parts from austenitic steels. It can be seen in Fig. 2, which presents the fragments of the chip formation process in the free orthogonal cutting 12H15G9ND steel, strengthened with transverse compression in the medium of rapeseed oil (a) and sulphofrezol P (b). Improvement of machinability of this steel is also characterized by a smaller radius of the curl of the latter by 28 %.

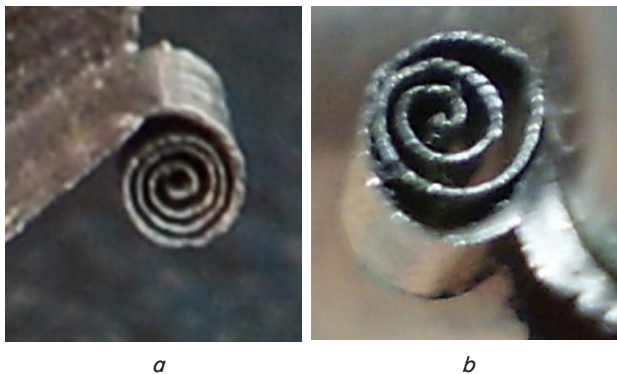


Рис. 2. Fragments of chip formation at free orthogonal cutting of 12Kh15G9ND steel (AISI 201), strengthened by the scheme of transversal compression with the deformation of 46 %: a – in the medium of rapeseed oil; b – of sulphofrezol P

Thus, there are grounds to recommend precise thermal treatment as the final operation for returning initial properties of parts from austenitic steels (high heat, corrosion and wear resistance).

4. 2. Research into the influence of surface reliefs of parts on operational properties

The creation of micro- and macroreliefs on the treated surface of parts is considered as a fragmentation of this surface. In physical micromechanics, this is a part of synergetic (self-organization process). Depending on the configuration and the type of fragments, the position as for physical properties of the material during tension and compression is proposed. Dimensions of the fragments, the time before destruction and the amount of critical deformation are predicted [6].

The fragments of the surface of a regular micro- and macrorelief (discreteness, the depth and profile of grooves) are determined in advance. Two methods for obtaining the grooves are used: cutting with a blade or an abrasive tool and deepening the linear indenters. In this case, two functions of the grooves are implied: technological and operational.

The technological function of regular micro- and macroreliefs implies the previous forced division of the cut allowances by grooves in the processes of machining deep openings of parts from plastic materials (steel, brass, aluminum alloys). Then, strong drain chips are formed.

The following contact phenomenon lies at the basis of the method for obtaining ring grooves for separation of chips. A ring-like groove is formed on the surface after a stop and subsequent restarting of this process. It reproduces the profile of the deforming element in the upper part area. If we place a dividing element of the optimal profile between the deforming ring and the tooth of the combined broaching, this will make it possible to get a deeper groove. At the static additional loading of a dividing element, the depth of the groove can reach 0.2 mm.

Fig. 3 shows the scheme of combined broaching with the ring indenter located on the broach

Table 1

Influence of preliminary cold plastic deformation and the type of lubricating-cooling liquid on chips shrinkage ξ and full length of the chip contact with the front surface of instrument c

| Brand of steel | Cold plastic deformation, $\varepsilon=46\%$ | Lubricating and cooling liquid | | | | | | | | | |
|------------------------|--|--------------------------------|-----------------|-----------------|-----------------|--------------|-----------------|----------|-----------------|---------------|-----------------|
| | | Without lubricant | | Sulpho-frezol P | | Rapeseed oil | | Flax oil | | Sunflower oil | |
| | | ξ | $c, \text{ mm}$ | ξ | $c, \text{ mm}$ | ξ | $c, \text{ mm}$ | ξ | $c, \text{ mm}$ | ξ | $c, \text{ mm}$ |
| 12Kh-15G9ND (AISI 201) | Non-strengthened HV=3.70 GPa | 3.9 | 0.19 | 2.85 | 0.12 | 2.34 | 0.09 | 2.44 | 0.10 | 2.36 | 0.09 |
| | Strengthened HV=4.96 GPa | 3.2 | 0.14 | 2.68 | 0.11 | 2.15 | 0.08 | 2.17 | 0.08 | 2.28 | 0.08 |
| 08Kh18H10 (AISI 304) | Non-strengthened HV=2.32 GPa | 4.2 | 0.22 | 2.91 | 0.12 | 2.41 | 0.09 | 2.50 | 0.10 | 2.43 | 0.10 |
| | Strengthened HV=3.85 GPa | 3.6 | 0.17 | 2.76 | 0.11 | 2.25 | 0.08 | 2.26 | 0.08 | 2.36 | 0.09 |
| 110G13L (A128) | Non-strengthened HV=6.00 GPa | 5.1 | 0.29 | 3.75 | 0.18 | 3.31 | 0.15 | 3.35 | 0.15 | 3.36 | 0.15 |
| | Strengthened HV=3.85 GPa | 4.5 | 0.24 | 3.56 | 0.17 | 3.13 | 0.14 | 3.15 | 0.14 | 3.25 | 0.14 |

It is necessary to intensify the processes by ultrasound or to apply combined broaching with rotating elements in order to obtain the technological grooves of increased depth

Another purpose of regular relief is the operational one. In this case, reliefs are used for manufacturing the parts of sliding friction couples. Such couples operate under the pressure of a working body: hydraulic and pneumatic cylinders, dampers, shaft mounting prop, piston and plunger couples of internal combustion engines, compressors, pumps, etc. In this case, the grooves serve as capacities for lubricants, labyrinths for compaction of friction couples and others. If cold plastic deformation is applied, the reliefs on the surface of the parts can be obtained by a combination of deforming broaching with ball rolling. In this case, the tool is equipped with a relief deforming element, which creates the longitudinal grooves, and ball rolling creates the groove in the direction of the feed. Filling the laby-

rings with solid lubricant within one tool pass is possible simultaneously with relief formation. Regular microreliefs can also be formed by deforming broaching.

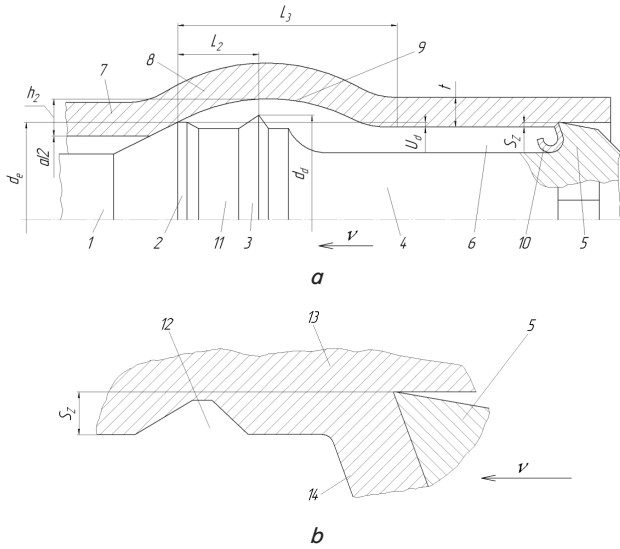


Fig. 3. The scheme of combined broaching: *a* – a tool with a ring indenter; *b* – a division of allowance by a groove; 1, 11 – distance bushings; 2 – a deforming ring; 3 – a divider; 4 – a cutting part with a tooth 5; 6 – an elongated chip groove; 7 – a workpiece of a hollow tubular parts; 8 – a movable section of elastic-plastic deformation; 9 – a surface of a wave of outcontact deformation with length L_3 , distance to maximum L_2 and height h_2 ; 10 – a roller of chips; 12 – a ring chip-like groove; 13 – a part; 14 – chips. Components of the process and the tool: v – velocity and direction of the instrument motion; S_z – allowance; t – the thickness of the wall of a workpiece; $a/2$ – tension; U_d – elastic restoration of a part; d_e and d_d – diameters relative to a deforming ring and a divider

The reliefs for operational purposes are used for manufacturing shrapnel shells of fighting parts of active and reactive projectiles, mines, aerial bombs, grenades [2, 7]. To obtain longitudinal and spiral grooves of the depth of up to 3 mm, by which a part is divided into shrapnel at the explosive substance initiation, it was proposed to use reduction. This method involves pushing a tubular workpiece together with the former through the hard alloy matrix. The former has longitudinal ledges of the triangular shape. The grooves on the inside part of the aviation bomb shell were obtained in this way (Fig. 4).

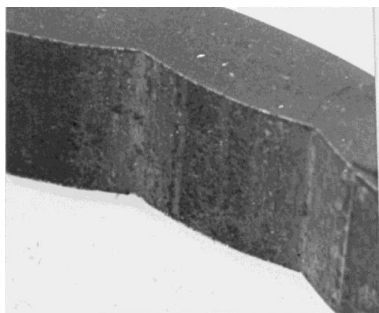


Fig. 4. Fragment of the inside part of the body of aviation bomb with longitudinal grooves, obtained by reduction

It is recommended to obtain spiral grooves for preliminary formation of shrapnel of hand grenades by the proposed method with the broaching tool that is equipped by self-rotating elements. The elements form the left and right intersecting spiral grooves at the longitudinal motion of this tool.

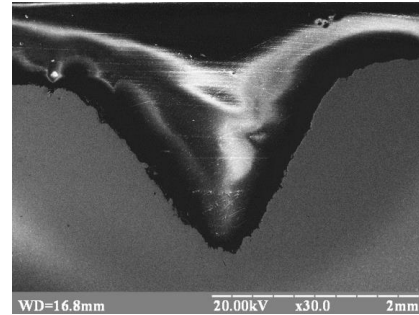


Fig. 5. Microphotograph of a groove obtained by immersion of a triangular linear indenter (steel R6M5, HRC 66) in a sample of steel 30HGSA, the groove depth is 2 mm, top angle is 60°

Experiments on the study of the method of obtaining the grooves (Fig. 5) of the depth of 0.005–5 mm by the method of cold deformation were conducted on the hydroficated presses with the force of 0.2 MN and 63 MN (model D-2238). A horizontally-broaching machine of model 7B56 was also used. Triangular linear indenters from fast-cutting steel R6M5 with top angles of 30°–90° and the top rounding radius of 0.005 mm served as tools.

4.3. Research into the effect of operational mechanism of protective film coatings on operational properties of bearings

Rolling bearings are widely used in friction nodes of machines. These nodes often work in chemically active media (gases or fluids). Rolling bearings are usually made from chromic steels. In this case, steel SH15; SH15S; SH15V and 18HGT are used. The hardness of these parts is within HRC 61...65. The hardness of balls should be equal to 63...67 HRC. Heterogeneity in hardness within one ring should not exceed 3 HRC. If a rolling bearing is used to work at elevated temperatures, the rolling bearing is tempered at temperatures of over 150 °C (by 50 °C higher than operating temperatures) to ensure the part size stabilization.

Chromic steels are thermodynamically unstable, that is, causing tribochemical reactions, which are an integral part of friction of solids.

The essence of the triboprocesses is that these processes flow under conditions of pulse force action and are accompanied by dissipation of mechanical energy. There are two main channels of irreversible dissipation of mechanical energy in the process of friction: tribochemical and rheological. Their development is determined by a number of factors: environmental properties, parameters of external load and the nature of a friction couple. Rheology, that is the theory of viscous elasticity or the generalization of the theory of elasticity and hydrodynamics of viscous fluid is the analytical basis to describe different types of deformation and fluidity of substances. The particles of energy dissipated and stored by a surface-active layer determine kinetics of accumulation of damage and destruction. All of this applies to rolling bearings as a characteristic model of a rolling couple.

The roughness of the surface of normal rolling bearings by the Ra parameter should not: be higher than 1.25 over the surface of the opening; be higher than 0.63 and 1.25 on the outer surface at the ring diameter up to 80 mm and 80–250 mm, respectively.

As we see, all kinds of steel, used for manufacturing rings and rolling bodies, are alloyed by quite a high amount of chrome (1–1.5%). Such chromic kinds of steel, in addition to high wear resistance, are also characterized by good machinability, grinding and reception of modification by the surface engineering methods.

Theoretical and calculation part of the study was the following. To solve the problem of load distribution between rolling bodies (balls) in rolling bearings, the variation-experimental method was proposed for the first time. In this case, the following assumptions were made: the base of the balls, on which the outer ring of the rolling bearing rested, was replaced by the continuous basis with equivalent compliance. Equivalence was considered to be of high-quality. Coefficient of force concentration on the balls and the pressure in the equivalent scheme were considered to be equal.

Solution of the equations of system equilibrium showed the effectiveness of the variation method for determining the function of load distribution on the rolling bodies.

Using the method in practice, we studied the bearings of series 208 with dimensions: diameter of the opening of 40 mm; outer diameter of 80 mm; width of 18 mm. Load Q was passed through the shaft with the diameter of 40 mm on the manual hydraulic press, and displacement u_0 was measured with precision of 0.01 mm. The results of measuring Q , which caused displacement u_0 are shown below in Table 2.

Table 2

Value of force Q and displacement u_0 of rolling bearings

| No. of experiment | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
|-------------------|------|-----|------|------|------|------|------|------|------|-------|
| Q , kg | 100 | 200 | 300 | 400 | 500 | 600 | 700 | 800 | 900 | 1,000 |
| u_0 , mm | 0.68 | 0.8 | 0.93 | 1.03 | 1.12 | 1.24 | 1.35 | 1.44 | 1.57 | 1.67 |

Comparison of concentration coefficients for the studied bearings of series 208 with 9 balls of rolling, obtained by the theoretical and variation-experimental methods showed the difference of less than 1%, that is, almost a complete match.

Another measure to increase reliability of rolling bearings was technological one [8]. In order to get a high-quality surface of parts, it is necessary to apply the methods of surface engineering, among which one of the most effective is ion nitriding. This is because nitriding is the finishing operation [9, 10].

At ion nitriding, in contrast to the processes of classical nitriding, the replacement of hydrogen with the argon arch-nitric mix makes it possible to get rid of hydrogen crumbling and, as a consequence, deterioration of the mechanical properties of the core of parts. A high quality of the surface layer and the base in the process of ionic nitriding is achieved by using them at the temperatures that are lower than the temperatures of high tempering. This excludes deformations of a part. An important role is also played by high energy of particle flux that is condensed on the surface. Due to this, the conditions that ensure the formation of nitrides in microvolumes of the surface layer are created. Ferrite and austenite of steel are strengthened due to nitrogen dissolving in the latter.

Thus, ionic nitriding in case of its application in the technology of obtaining the main parts of bearings (rings and balls) performs a dual role. On the one hand, a protective layer is formed on these parts without changing their dimensions and roughness. It does not allow harmful elements, first of all oxygen, to penetrate from outside. In addition, due to the formation of nitrides and strengthening of ferrite or austenitic, the surface layer of the corresponding parts of bearings gets additional strengthening.

To implement the process of nitriding, the unstable (positive) section FG of volt-ampere characteristics, so-called area of the strong-flux glow discharge is used [8] (Fig. 6).

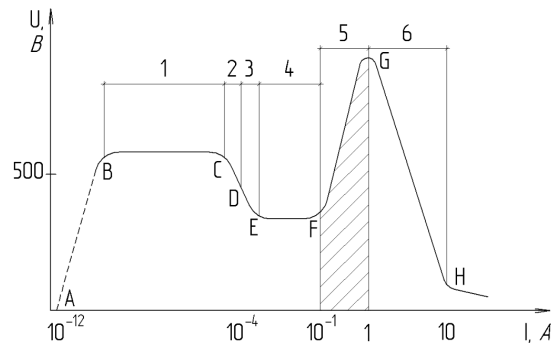


Fig. 6. The typical voltage-ampere characteristics:

- 1 (BC) – Townsend discharge; 2 (CD) – crown discharge;
- 3 (DE) – subnormal glow discharge; 4 (EF) – normal electric glow discharge;
- 5 (FG) – abnormal electric glow discharge;
- 6 (GH) – arc discharge

The processes that occur on the surface of the cathode in the formation of gas ions can be classified as follows: emission of electrons; diffusion of atoms from the surface (evaporation); diffusion of ions to the surface layer of a part; efficiency of kinetic energy of the surface (heating) of the part. The ions that were accelerated in the area of falling of cathodic potential with large kinetic energy get on the surface of a part at some millimeters from the surface. In this case, 90% of energy of ions is converted into heat energy. Thus, plasma heats the part to the required temperature of nitriding. A significantly smaller part of kinetic energy of ions is necessary for pulling the atoms from the crystal lattice. Metals and metal alloys, as well as non-metallic materials, such as carbon, oxygen, nitrogen, etc., can evaporate. Formation of the nitride layer goes as follows: nitrogen atoms, rooted in the surface layer of the material, subsequently diffuse through grain boundaries and, actually, through grains. Depending on the duration of treatment and the parameters of the nitriding process, a corresponding concentration profile occurs. During ion nitriding in the pulse mode, nitrogen diffusion goes as follows: if on the surface of the layer the nitrogen concentration reaches the magnitude required for the formation of γ' - or ϵ -nitride, then these very nitrides are formed. The latter are formed from individual nuclei and form a dense layer, the so-called “connection layer”.

The thickness of the nitride layer, regardless of the content of nitrogen increases as a result of nitrogen penetration in accordance with the second Fick’s law [2, 8].

At the same time, diffusion of nitrogen atoms through a layer of compounds into the depth of metal continues. In this case, the rate of diffusion through the γ' -phase is by about 25 times lower than that through ferrite. A diffusing layer of carbon during nitriding remains in the layer of compounds,

where this layer is absorbed by created nitrides. The boundaries of the grains, in which carbides are located, expand as a result of nitrogen absorption [2].

Nitrogen in plasma is in atomic chemically active state. Iron nitrides, saturated with nitrogen, are formed in front of the cathode surface. FeN molecules are condensed on the surface of a part and dissociate to form ferrum nitrides of the lower order Fe₂N, Fe₃N and Fe₄N. In this case, nitrogen is released, diffuses in a part, or being evaporated, comes back into plasma.

The rate of ion nitriding is the “Achilles’ heel” of the process, because it is only 0.01–0.02 mm of an increase in the thickness of the nitrided layer per hour. This is because all known schemes of improvement of nitriding are practically exhausted. This concerns the composition of gas medium, pressure, temperature, characteristics of glow discharge, the algorithm of preparation to the process and conducting the process itself, as well as design parameters of the plant. However, it has no significant importance in the case of the creation of a protective nitrided layer on races and bodies of rolling bearing. This is because the thickness of the protective layer can be measured in micrometers or parts of a micrometer.

The modes of ion nitriding were as follows: temperature was 530–550 °C; pressure was 87 Pa; voltage was 400 V; current power was 12 A; the medium was the mixture of nitrogen (N₂ – 80 %) and argon (Ar – 20 %). The power circuit, which operates in the pulse mode at the frequency of 100 Hz, was developed to provide the working temperature, lower than the temperature of high tempering. To prevent the conversion of the metastable glow discharge into the undesired stable arc discharge in the nitriding plant, it was proposed to use the fast-rate relay. This prevents any damage to the surface of a strengthened part.

It should be noted that during the implementation of hydrogen-free nitriding of rolling bearings, a special attention should be paid to preliminary preparation of the surface. It is necessary to remove all remnants of the pollutants before the operation. Washing in the washing machine with the use of ultrasound is most suitable. In this case, fitting surfaces (external and internal) of rolling bearings, the roughness of which is Ra<2.5 and Rz<20 should not be protected because they themselves work under conditions of fretting-wearing. Due to this fact nitriding increases the wear resistance of these surfaces.

4. 4. Research into influence of waviness of surfaces of deep openings on the properties of parts

Operational bodies of a hydraulic system of a machine are power and manipulation hydraulic cylinders. The most complex part of the latter from the position of manufacturing and repairs is the sleeve, since it belongs to the class of the deep ones. The surface of the opening must meet the tough requirements in terms of accuracy: non-roundness within H7-N9 and the deviation from straightness of generatrix up to 0.25 mm per 1000 mm of the length of an opening, as well as roughness of machined surface Ra 0.05–0.15 microns.

The influence of physical-mechanical and geometric properties of the surface after the combined deforming-cutting broaching on the machinability of sleeves is the following: the thickness of cold strengthening and texture of the surface layer reaches 0.2 mm, and friction coefficient on the back surface of the tooth of broaching is decreased by the previous cold plastic strengthening from 0.5–0.7 to

0.2–0.35. Favorable tangential residual stresses of the first kind occur in the surface layer.

Waviness factor is of great importance for the surface of sleeves of hydrocylinders, since it ultimately affects the unwanted leakage and flowing of working fluid from the system. Waviness is not always paid attention to in the existing processes (Fig. 7).

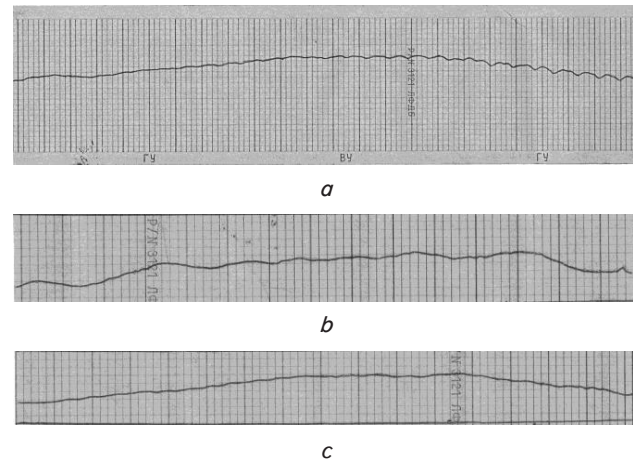


Fig. 7. Examples of waviness of the surface of finished sleeves of hydrocylinders, produced by the operating plant technology BU1000, GU5: *a* – TMZ, town of Turbiv; *b* – “AgroMasterPlus” LTD, city of Melitopol (Ukraine); *c* – Pipe workpiece, Romania

In all cases, waviness is explained by the interference of roughness maxima from several kinds of treatment, since the direction of the major movements of all these operations is the same. The experiments on the bench based on the broaching machine of 7B57 model and the horizontally boring machine showed that the use of combined machining eliminates the waviness of the machined surface by changing the main movements of broaching and rolling by 90°.

5. Discussion of results of studying the improvement of operational properties of parts

To enhance machinability of austenitic steel as the main structural material and the material of protective coating, it is recommended to use the preliminary cubic cold plastic deformation with the use of environmentally friendly lubricants of plant origin. This combination makes it possible to obtain a joint positive effect during cutting on the part of the zone of chip formation and the contact area on the front surface of the tool. The improvement of machinability during using preliminary cold plastic deformation is explained by increased density of dislocations. Their association leads to emerging micro cracks in the machined material and structural transformations of the latter. It is recommended to use precise finishing heat treatment in order to return the initial high operational properties of the products from austenitic steel.

The peculiarity of a combination of preliminary cold plastic deformation with environmentally friendly lubricants of vegetable origin, in particular with the modified rapeseed oil, is explained by positive joint action of these two technological factors. The effect of the former facilitates processes in the area of chip formation (the volume of the zone de-

creases by 20–40 %), and the action of the latter positively affects the contact processes on the front surface of the tool by decreasing the friction intensity. Thus, friction coefficient decreases by 1.5–5 times. Limitations of the study of the improvement of machinability of austenitic steels are related to choosing only 3 brands of these steels, alloyed with chromium, manganese and nickel. At the same time, there is the number of brands of austenitic steels that is by an order of magnitude higher.

The method of immersion of the tempered linear indenter from fast-cutting steel is implemented by cold plastic deformation of samples from plastic materials (steel, brass, deformed aluminum alloys, etc.). The method enables obtaining the grooves of triangular profile of the depth of 0.005–5 mm with the top angles of 30–90°, that serve as the basis for regular micro- and macroreliefs for the technological and operational purposes.

The advantages of the method for the formation of regular micro- and macroreliefs are in the possibility to obtain them by the method of cold deformation, rather than by cutting with a blade or an abrasive tool. The method involves not only ensuring the depth and the desired profile, but also strengthening the material at the basis of a groove. However, the research also requires examining the entire range of possible grooves for various purposes.

Ionic-pulse nitriding was proposed and studied as a technological measure for improving reliability of bearings of rolling. The method is the finishing operation in machining rings and balls of bearings. The role of nitriding is dual: creation of a protective surface layer that prevents harmful substances from the external environment from penetrating into products and increasing the surface hardness. This eventually leads to the improvement of reliability of rolling bearings.

However, ionic-pulsed nitriding is the method, used to obtain vacuum film coatings for different purposes, which increase wear, heat, corrosion resistance, the appearance of parts, etc. Based on this, it was necessary to continue the study of film coatings, especially in the use of Mo, Al, Ta, Nb compounds and other compositions. Exploration of these coatings as solid lubricants in friction couples and protection of products from elevated temperatures, such as blades of gas turbines, is promising.

To eliminate the negative effect of heredity of the related mechanical operations on the geometric characteristics of machined surface, it is recommended to change the direction

of the major movements of operations by 90°. Results of the study, presented in the article, may become the basis, as a minimum, for the creation of four technologies of production of corresponding machine parts.

6. Conclusions

1. The following sequence of operations to improve machinability of paramagnetic austenitic steels was determined: cold volume plastic deformation by method of transversal compression with deformations of 40–90 % – cutting by blade tool – returning initial operational properties of parts by precision heat treatment.

2. The typical methods for obtaining regular micro- and macroreliefs of the technological and operational purposes by the broaching tool and reduction of formers, were developed. The method for obtaining the ring grooves for chips division was based on the contact phenomenon that accompanies short-time stops (0.2–0.4 s) and restoration of broaching. In this case, a groove of the depth of 0.02–0.05 mm is formed on the treated surface. A groove can be increased by depth by the ultrasonic or static additional loading up to 0.2 mm. Operating grooves of the depth of up to 3 mm are obtained by the method of reduction on the formers.

3. The problem of load distribution between the rolling bodies in rolling bearings was solved by the variation-experimental method and improvement of operational properties of the bearings by applying protective film coatings. These coatings of thickness of 0.002–0.01 mm protect the race and the body of rolling bearings. The protective role of coatings involves healing microcracks from grinding and increasing hardness, therefore, wear resistance of surfaces of high-load parts.

4. The technological method for reducing waviness of the surface of deep openings of the sleeve-like parts by the change of directions of the main operations of machining was determined. These operations are performed by the form creating deformation-cutting broaching, which moves mainly along the part. The process is characterized by the formation of the system of longitudinal micro non-uniformities and waviness of the machined surface from the system “machine – device – tool – part”. To eliminate these errors of the machined surface, it is recommended to change the main motion for the following operation of plugging at $\pi/2$ to the axis of a detail.

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В даному дослідженні вивчено вплив безфторидних розчинів, включаючи 8 М NaOH, 0,8, 1,6 і 2,4 М H₂SO₄ та 0,1, 0,4 і 0,8 М HClO₄, на збільшення вмісту оксиду танталу і ніобію в результаті вилуговування. Перед вилуговуванням олов'яний шлак Бангка (ОШБ) характеризувався за допомогою РФА. Потім шлак обжарювався при 900 °С, гартувався і зневоднювався. Далі ОШБ пройшов процес просіювання з розмірною класифікацією +100, –100 +150, –150 +200, –200 +250 і –250 меш. Після цього шлак –200 +250 меш витравлювали за допомогою 8 М NaOH. Потім вилужений продукт ділили на два, один з яких витравлювали з використанням 0,1, 0,4 і 0,8 М HClO₄, а решту – за допомогою 0,8 М HClO₄, а потім 0, 0,8, 1,6 та 2,4 М H₂SO₄ при 25 °С протягом двох годин. Для характеристики всіх залишків використовувався РФА, а для фільтратів – ААС, а також ІСП-ОЕС. Дане дослідження обумовлене дефіцитом танталу і його статусом як одного з найважливіших технологічних елементів. На додаток, більшість попередніх досліджень дозволили збільшити вміст оксиду танталу і ніобію завдяки використанню фторидної кислоти, в той час як в даному дослідженні розглянуті тільки безфторидні розчини. Результати показують, що перхлоратна кислота з подальшим вилуговуванням сірчаною кислотою злегка підвищує вміст танталу і ніобію. Однак цей метод є найбільш ефективним серед NaOH, HClO₄ і H₂SO₄ з подальшим вилуговуванням за допомогою H₂SO₄. Даний висновок є формою наукових зусиль з підтримки наявності танталу за рахунок використання непотрібних відходів олов'яної плавки

Ключові слова: вилуговування, оксид ніобію танталу (ОНТ), олов'яний шлак Бангка, NaOH, HClO₄

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ENRICHMENT ON BANGKA TIN SLAG'S TANTALUM AND NIOBIUM OXIDE CONTENTS THROUGH NON-FLUORIDE PROCESS

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1. Introduction

The electronic, automotive, and aerospace new technology's high dependence on tantalum makes this metal one of the technology-critical elements [1]. Researches on the

endurance of tantalum supply chain investigated the endurance improvement mechanism such as optimization of other sources (e. g. tin slag, scraps, etc.), recycling, material substitution, and hoarding [2]. Efforts to widen the knowledge of tantalum around environment were done especially that