Scientific Journals
of the Maritime University of Szczecin

Zeszyty Naukowe
Akademii Morskiej w Szczecinie

2018, 54 (126), 28–34
ISSN 1733-8670 (Printed)
ISSN 2392-0378 (Online)
DOI: 10.17402/282

Received: 14.12.2017
Accepted: 28.03.2018
Published: 15.06.2018

Study of the impact of surface roughness on wear resistance of ship machinery and mechanisms

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Key words: ship machinery and mechanisms, details, treatment, methods, roughness, surface layer, wear

Abstract

The article deals with the influence of surface roughness, processed by various technological methods, on the wear-resistance characteristics of the surface layer of high-precision parts of ship machinery and mechanisms. It considers various technological methods of processing parts; rotary cutting, grinding with vibration damping, rotational honing, grinding with metered removal of surface material and elastic rolling.

It was found that the application of rotational boring as a method of finishing not only forms an additional, highly wear-resistant surface layer on the surface of the parts, but also provides high productivity. The process of grinding with vibration damping significantly reduces the transfer of abrasive particles to the surface being treated, and improves the accuracy, quality and wear resistance of the surface layer. On rotational honing, the discontinuity of the cutting of individual grains is combined with the continuity of the chip formation process; the metal does not adhere to the working surface of the cutting part of the tool, and the temperature in the cutting zone decreases, resulting in a high-quality, wear-resistant surface layer on the parts. When lapping with dosed removal of the material of the surface layer, the optimum thickness of the highly-deformable surface layer is ensured, due to the possibility of controlling the abrasive action on the surface to be treated, which promotes the formation of a reliable, wear-resistant layer. Elastic rolling allows processing of non-rigid, thin-walled parts by stable, balanced, controlled forces, without reducing their accuracy, quality and wear-resistant characteristics.

Introduction

Indicators of reliability and durability of ship machinery and mechanisms are evaluated and selected, taking into account the main characteristics of their operation modes, operating conditions, etc.

The probability of no-failure operation is a key and universal characteristic, meaning probability of no-failure of the object within the specified operating limits. The main and universal characteristic in the probability of failure-free operation of the object is the probability that, within a given operating time, the object's failure does not occur (Suleymanov, 2016).

Vessels of different designations are equipped with a variety of different machines and equipment, mechanisms and assemblies, devices and tools, whose reliability is the main factor both in ensuring the safety of people and their property, and in fulfilling the various technological tasks set.

Ships' machinery and mechanisms vary considerably in purpose, and they execute numerous diverse technological tasks. Their machinery and mechanisms operate in different atmospheric and climatic conditions. Their components are significantly influenced by moisture, heat, cold, dust or sand, light, radiation, low and high pressure, salts of various types, seawater, etc.

Unforeseen accidental processes that arise from overload and operating conditions can also affect the performance of ships' machinery and mechanisms.

The materials from which they are made significantly influence the reliability of ships' machinery and mechanisms, particularly the wear resistance of their critical parts. Thus, the reliability of ships' machinery and mechanisms is significantly dependent on the wear resistance of critical parts and materials.

Wear is the result of the interaction of forces on friction surfaces and is one of the main factors in the analysis of physical and mechanical processes that occur on the surface layer of machine parts.

The wear of the surfaces of the parts is directly dependent on the size of the contact area and the pressure affecting this area. The rate of wear of the surface layer material also changes significantly due to pressure variations in the contact area of the surfaces of the parts.

Method of investigation and processing of obtained data

The elastic contact problem for rough surfaces was considered for the first time by Shtayerman (1949), and the linear law of deformation of the surface layer's micro-roughnesses (fine irregularities) was proposed.

However, experimental studies (Demkin, 1970) have demonstrated that dependence between the compression force and deformation of micro-roughness is non-linear.

In the work of Gasanov (2001), equations of the surfaces of interacting bodies of shaft and sleeve prior to deformation are written as:

$$y_1 = f_1(x); \;\; y_2 = -f_2(x) \tag{1}$$

At the point of genuine contact between shaft and sleeve, the origin of coordinates is established.

Under the action of compressing forces, the shaft assumes shift σ_1, sleeve – σ_2.

Points on the surface of the shaft and points on the surface of the sleeve respectively assume shifts v_1 and v_2 in the direction of the y-axis.

As the coordinates of the points of shaft and sleeve become identical on contact, the conditions of movement of the shaft and sleeve can be described as below:

$$-v_1 + f_1(x) - \delta_1 = v_2 - f_2(x) + \delta_2 \tag{2}$$

δ_1 – translational movement of the shaft points;
δ_2 – relevant points of the sleeve;
$f_1(x)$ – function describing the geometry of the shaft's surface;
$f_2(x)$ – function characterizing the geometry of the inner surface of the sleeve.

Values v_1 and v_2 characterize shift as a result of wear of the shaft and sleeve surfaces.

Using various methods, one can determine the amount of surface wear of both shaft and sleeve.

It is known that, when wear occurs as a consequence of various forces, the deterioration of the reliability indices of machines and mechanisms often follows a normal distribution.

A normal distribution is usually regarded as limiting for a Poisson distribution, binomial distribution, gamma-distribution, etc. (Gafarov et al., 2016).

A normal distribution is characterized by an integral function:

$$F(x) = \frac{1}{\sigma\sqrt{2\pi}} \int_{-\infty}^{x} \exp\left[-\frac{(x-\mu)^2}{2\sigma^2}\right] \mathrm{d}\,x \tag{3}$$

or density of distribution:

$$f(x) = \frac{1}{\sigma\sqrt{2\pi}} \exp\left[-\frac{(x-\mu)^2}{2\sigma^2}\right] \tag{4}$$

For normal distribution:

$$M(x) = \mu, \quad D(x) = \sigma^2, \quad V = \frac{\sigma}{\mu} \tag{5}$$

$-\infty < \mu < +\infty$ and $\sigma > 0$ – parameters of shift and scale.

If a change of random value is characterized only by positive values, one should take into account conditions of a truncated normal distribution and make some corrections in the calculations.

To determine changes in the value of the surface layer's wear, depending on the roughness of the surface details treated using different methods, and depending on the operating conditions of the machinery and mechanisms, one can use other laws of distribution and statistical methods.

The results of our investigations show that surfaces treated by different methods, despite identical conditions, differ both in the roughness of the surface and in the physical-mechanical characteristics of the surface layer. Defects identified by quality parameters of the surface layer later exert an impact on the wear-resistance of the contact surfaces of components. Wear-resistance characteristics of the contact surfaces of the friction (contacting) pair are directly related to the macro- and micro-geometry of the surfaces and applied loads. Wear of the surface takes place because of the cutting of micro-crests appearing after mechanical treatment.

Results of the study by Garkunov (1985) demonstrated that metal surfaces have roughness at the atomic level, and when in contact, they contact through the most prominent irregularities. With metals in an ordinary environment, dust particles act as such roughnesses. At low loads, they can absorb the major part, or even all, of the load entirely. A somewhat different situation arises if the individual contact areas are elastically deformed.

In most mechanical methods of processing, especially with abrasive tools, particles of the material of the tools are transferred to the surface to be treated, which leads to an intensification of the wear of the surface layer of the parts of the friction pair.

In manufacturing high-precision, critical parts of a ship's machinery and mechanisms, it is vitally important to choose appropriate methods of mechanical treatment, which will ensure the optimum parameters of roughness R_a, residual stress σ, micro-hardness H of the surface layer and high-abrasion-resistant characteristics of the contact surfaces.

Specimens treated by means of rotary boring, grinding with vibration damping, rotary honing, lapping with dosed removal of material of the surface layer and elastic rolling were used to determine the abrasion-resistance characteristics of the surfaces.

For the treatment, steels of grades 38CrMoAlA, steel 30Cr13, steel 40Cr and 45 were taken.

Specimens made from the above materials with the following dimensions were used in the experiments: outer surface diameter ϕ55 mm; inner surface diameter ϕ45 mm; length l = 300 mm. The precision of treated specimens was in the range of 8-th, 9-th surface finish.

The roughness of the surface layer was measured using a profiler – surface roughness recorder, model 201, with a record of profile diagram for treated surfaces.

A special device on the base of pumping unit CKN-5 was used for experimental study of the wear of details' surfaces. The test was carried out in similar conditions and operation modes for all tested specimens. The method of micrometric measurements was used to determine the amount of wear. Measurements were carried out using a micrometer, indicating bore gauge, and with the use of blade-optical instruments and a toolmaker's microscope. The accuracy of measurements, depending on the instrument, varied from 0.01 to 0.001 mm.

Base information

Our investigations have shown that the wear of specimens' surfaces significantly depends on the surface roughness R_a. An increase of the surface roughness R_a, treated by rotary boring, from 0.3 to 2.0 µm increases two-fold the wear of the surface layer W, i.e., up to 14 µm (Figure 1).

Specimens manufactured from various steels demonstrate different abrasion-resistance characteristics. For example, the wear of specimens manufactured from steel 38CrMoAlA is 3–4 µm less than the wear of specimens manufactured from steel 45. Despite identical conditions of treatment, the surface roughness of different grades of steel varies, which is directly related to the physical-mechanical properties of the materials used for manufacturing. The value of micro-hardness of the surface layer is also very important, as, despite the same kind of treatment for different materials, this parameter has different values and depths of occurrence in the surface layer material.

Hardness and wear are inversely related and, to improve wear resistance, it is also necessary to increase the micro-hardness of the surface layer. Rotary cutting is a power process and is characterized by large cutting-force components, which results in additional plastic deformations of the surface layer material of the specimen. By adjusting parameters of the cutting mode and geometry of the rotary tool, one can regulate in a wide enough range the roughness R_a, residual stress σ and micro-hardness H of the surface layer, which ensures low disposition to seizure and high long-term strength of details' surface (Figure 1).

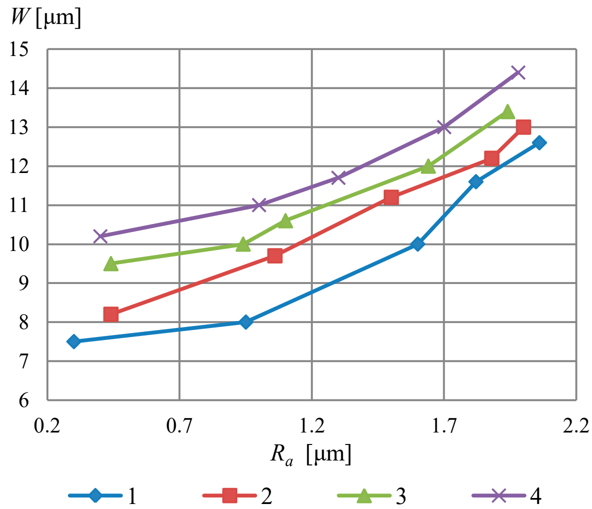

Figure 1. Dependence of wear of parts *W* on the surface roughness (processed by rotary cutting). 1, 2, 3, 4, respectively: Steel 38CrMoAlA, steel 30Cr13, steel 40Cr and steel 45

It is known (Garkunov, 1985) that the structural condition of metal is characterized by phase composition, type and character of crystal lattice, and the number, nature and distribution of defects. The resistance of metals to wear is largely determined by the structure and combination of the properties of local micro-volumes. A significant influence on wear resistance is exerted by the crystal lattice and the orientation of the sliding direction in friction with respect to different crystalline directions.

These characteristics and their main indices are mainly formed during the process of mechanical treatment of details. Thus, selection of the specific treatment method and establishment of optimum treatment regimes are important for obtaining the required abrasion-resistance characteristics of components' surfaces. The use of rotary cutting as finishing both forms an additionally deformed, high-abrasion-resistance surface layer on the components' surface and, at the same time, ensures high productivity. Rotary cutting can be used both as a preliminary and as a final technological operation.

Dependence of the wear of surface layer W on roughness R_a of the surface of specimens treated by grinding with vibration damping is shown in Figure 2.

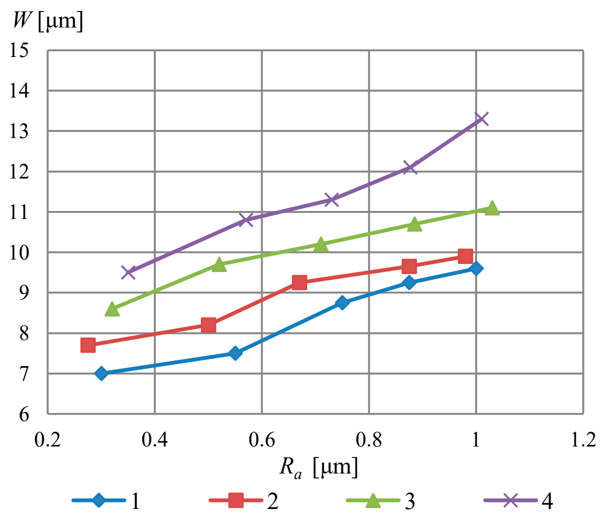

Figure 2. Dependence of wear on parts *W* on surface roughness (processed by grinding with vibration damping). 1, 2, 3, 4, respectively: 38CrMoAlA, steel 30Cr13, steel 40Cr and steel 45

Analysis of experimental results shows that intensity of wear of the surface of specimens treated by grinding with vibration damping is slightly less than when processed by rotary cutting. Relatively low intensity of wear in this case is related to the lesser value of the surface roughness on grinding with vibration damping. Other physical-mechanical characteristics of the surfaces treated using rotary cutting and grinding with vibration damping are practically identical. Residual tensile stresses and identical micro-hardness of the surface layer are characteristic of rotary cutting and grinding with vibration damping.

Results of numerous studies have demonstrated that, during ordinary grinding, particles of material from the abrasive disk are transferred to the treated surface. This feature is also characteristic of grinding with vibration damping, but with lower intensity owing to the damping of vibrations.

Transfer of particles from the abrasive disk is often one of the main reasons for cutting or scratching of the material's surface layer. Intensive scratching (abrasion) creates additional spots of tension in the surface layer. As residual tensile stresses are also characteristic of the grinding process, due to high temperature in the area of cutting, intensive wear of the surface treated by grinding with vibration damping, rather than "cold" treatment methods (honing, lapping, and flattening), is to be expected.

Also, abrasive particles implanted on treated surfaces in the process of grinding are transferred onto the contact surfaces of the other member of a friction pair and scratch them.

Considering the above, when choosing a friction pair, it is necessary to account for the materials of the components, the precision and quality of the surface layer and the methods of treatment of the contact (mating) surfaces. Occasionally, a particular method of treatment might be the only one able to achieve the required accuracy, surface quality and wear resistance.

From this point of view, the proposed process – grinding with vibration damping – is one of the advanced mechanical treatment methods, allowing significant reduction of the transfer of abrasive particles to the treated surface, improving the precision and quality of the surface, and improving wear-resisting characteristics of the surface layer owing to the significant reduction of vibrations arising in the course of the operation.

One of the advanced methods of mechanical treatment significantly improving the wear resistance of the working surfaces of components is rotary honing (Gafarov & Babayev, 1999; Gafarov et al., 2015).

The distinctive feature of rotary honing, compared with ordinary honing, is the additional working motion of the cutting part (wheel) of the rotary head.

With the usual methods of honing, there are three main motions: rotary with velocity V_{rot} around the axis of the opening being treated; reciprocating motion along the axis of the treated opening with velocity V_{recip}; as well as radial motion of the bars with velocity V_{rad}, while metal from the surface layer is removed. In the case of rotary honing of openings, diamond-dressing wheels self-rotate around their axis with angular velocity ω_p (Gafarov et al., 2015), whilst the rate of self-rotation of the diamond-dressing wheel is several times higher than the rotation rate of the lathe spindle. In the process of treatment, the working surface of the diamond-dressing wheel is continuously renewed, due to its rotation around its own axis.

One of the main advantages of rotary honing is the fact that, during a dry run, the cutting element of the diamond-dressing wheel is continuously washed with lubricating, cooling liquid which, in the process of treatment, takes away treatment wastes, including diamond particles. This process significantly reduces the transfer of diamond particles to the working surface of components, improving the wear-resistant characteristics of the surface layer.

The impact of roughness R_a of the surface layer treated by rotary honing on wear of the surface W of components is shown in Figure 3.

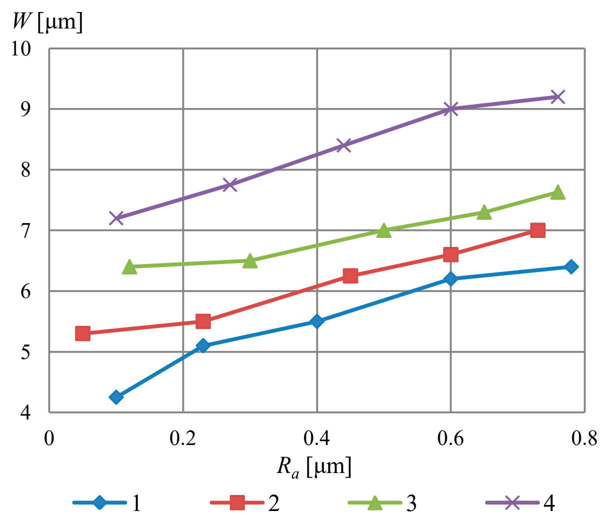

Figure 3. Dependence of wear on parts W on the roughness of the surface (processed by rotational honing). 1, 2, 3, 4, respectively: 38CrMoAlA, steel 30Cr13, steel 40Cr and steel 45

As can be seen from Figure 3, the intensity of wear of the surface of components treated using rotary honing is significantly less, compared with previously discussed treatment methods. For example, at increase of the surface roughness R_a from 0.10 µm to 0.70 µm, wear of the component's surfaces increases for steel 38CrMoAlA approximately by 4–6 µm; for steel 30Cr13 by 5–7 µm; for steel 40Cr by 6–7 µm; for steel 45 by 7–10 µm.

The main disadvantage of ordinary diamond honing is cutting of the bond by the continuous descending flow of chips and other adhesive materials on the steel being treated. This disadvantage is avoided with rotary honing: chips are thrown out of the cutting zone owing to linear contact of the tool with the component. Simultaneously, the intensity of adhesive and diffusion wear of the diamonds is reduced, due to the short-term nature of the contact and more efficient cooling of the wheels; the temperature of the workpiece is also reduced, resulting in the formation of residual stresses in the surface layer, significantly improving the wear resistance of the contact surfaces.

The discontinuity of cutting individual grains on rotary honing combines with the continuous process of chip formation, so that there is practically no sticking of metal on the working surface of diamond wheels. This contributes to a reduction of temperature in the cutting zone, thus leading to improvement of the physical-mechanical properties of the surface layer and wear resistance of the components' surfaces.

Results of investigations show that, with similar roughness of surfaces treated using lapping with dosed removal of material of the surface layer, the wear resistance of components manufactured from various grades of steel varies (Figure 4).

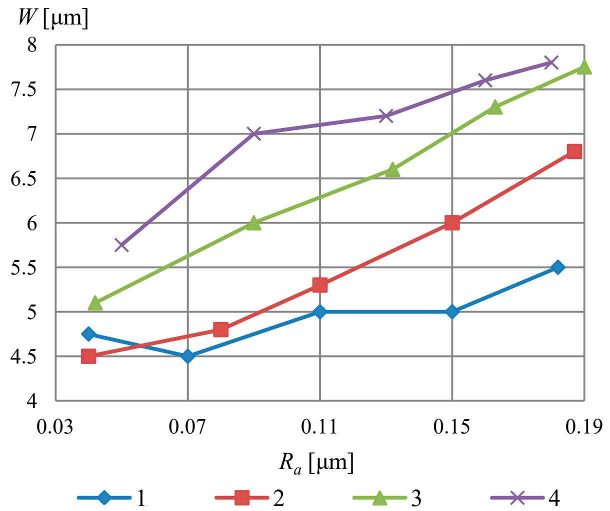

Figure 4. Dependence of wear of parts W on the surface roughness (processed by dosed lapping). 1, 2, 3, 4, respectively: 38CrMoAlA, steel 30Cr13, steel 40Cr and steel 45

On increase of roughness R_a from 0.035 to 0.075 µm, wear W of components' surfaces increases insignificantly or practically does not change. With further increase of initial roughness, wear of surfaces also increases.

Lapping with dosed removal of material of the surface layer, like ordinary lapping (grinding-in) is an abrasive method of finishing. Abrasive particles in grinding (lapping) pastes have various geometrical forms. A specific feature of this method is that it is used only as a final operation. Allowances for machining, grinding paste, accuracy of machining, quality of the surface and its components, time of treatment and other parameters are established in advance. Special procedures, designs of cutting tools and engineering accessories are developed for the implementation of this method. The presence of sharp cutting edges and accuracy of the form of abrasive particles do not influence formation of the surface layer, and wear particles make up a certain volume of the formed asperities. Abrasive action is reduced to cutting or scratching and asperities formed in the surface layer do not exceed the size of the abrasive particles in the grinding paste.

On lapping with dosed removal of material of the surface layer, the optimal thickness of the deformed surface layer is achieved, owing to the possibility of controlling the abrasive action on the treated surface, which allows the formation of a reliable, wear-resisting surface layer on the components. Asperities are formed on the surface layer under the action of local deformations of particles and depend on the condition of previously prepared surfaces under lapping. Depending on requirements of the quality of the surface, initial deformations can be removed fully or partially.

Results of our investigations demonstrate that cutting and scratching are not always characteristic of frictional interfaces. At high sliding velocities, the material of the surface layer softens due to high temperatures developing in the zone of contact between the surfaces. As a result, elastic flow predominates over cutting and scratching.

A key factor determining the wear-resisting characteristics of the surface layer of machine components is surface roughness R_a and its main components. By regulating technological parameters of the process of lapping with dosed removal of material of the surface layer, we can obtain optimum micro-relief of the contact surfaces, which ensures the maximum wear resistance of components of ships' machinery and mechanisms. Results of extensive observations show that the quality of the surface layer, accuracy of the gaps between the members of the friction pair, thickness of the oil film, length of bearing area, distribution of load along the contact surfaces, etc. are key parameters characterizing wear resistance of component surfaces of friction pairs in ships' machinery and mechanisms.

One of the key methods of mechanical treatment significantly improving the wear resistance of components' surfaces is rolling or flattening. The process of rolling can be compared with such methods of finishing as diamond smoothing, honing, fine grinding (polishing), fine lathe turning, polishing or super-finishing. However, a significant disadvantage of the rolling process is that it is characterized by high strength, which does not allow its application when treating high-precision flex, thin-walled details, such as eyes, sliding bearings, thin-walled bushings, etc. When using the rolling method, it is necessary to take into account the dimensions and shapes of the surfaces to be machined, the strength and rigidity of the parts, the requirements for the accuracy and quality of the surfaces, the thinness of the parts, etc.

By principle of the interaction between working elements of the tool with the treated surface, rolling heads are divided into two types. With the first type of treatment, the working elements of the head slide along the treated surface. With the second type, mechanical action on the treated surface is accomplished by two motions of components or tools, by rolling of the working elements of the head along the treated surface. One such method is rolling with balls or wheels. To reduce the harmful influence of increased treatment forces of rolling on the precision and quality of critical, non-rigid, thin-walled components, a special technique has been developed called elastic lapping. A specific feature of elastic lapping is the fact that deforming elements of the roll head are located on a special dosing-regulating device, which allows rolling the surfaces of components with stable, balanced treatment forces (Gafarov & Abbasova, 2006; Gafarov, Suleymanov & Kalbiyev, 2013.

Elastic rolling allows treating the surfaces of non-rigid, thin-walled components without compromising their accuracy and quality characteristics. This method can be successfully used for treatment of the outer surfaces of components.

Results of investigation of the effect of roughness R_a of rolled surfaces on wear resistance W of the surface layer are presented in Figure 5. As follows from Figure 5, surfaces being treated by elastic rolling demonstrate the best wear-resistance characteristics compared to other investigated methods of finishing. An increase of roughness R_a within the range of 0.02 to 0.08 μm actually does not have a noticeable effect on a reduction or increase of surface wear W. A minor increase of wear of the surface layer is observed on the increase of surface roughness above 0.10 μm. Steels of grades 38CrMoAl and 30Cr13 possess the best wear resistance characteristics, steel 45 the least.

The developed method allows one or another processing mode to be applied depending on the

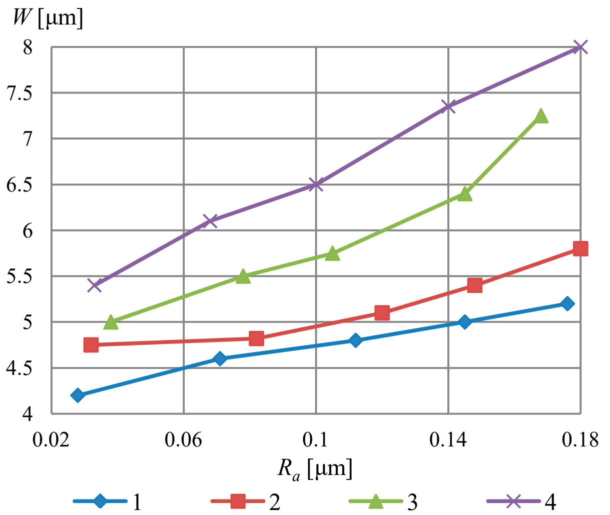

Figure 5. Dependence of wear on parts and on the roughness of the surface (processed by elastic rolling). 1, 2, 3, 4, respectively: 38CrMoAlA, steel 30Cr13, steel 40Cr and steel 45

requirements for quality and wear resistance of the surface layer, which can be achieved by optimization of the main technological parameters.

Conclusions

It should be noted that increasing the hardness of the surface layer does not always ensure the highest wear resistance. Consequently, it is necessary to carry out step-by-step preparation of high-abrasion-resistant surfaces of components. Selection of the optimum combinations of technological operations is very important. One of the key preconditions defining the highest wear resistance of components' surfaces is the combination of hardness with precision, roughness and physical-mechanical properties of the surface layer. The results of our investigations show that the best wear-resistant surfaces were obtained when the surface layers of components were treated by different technological methods in terms of quality corresponding to the surfaces after running-in. The equilibrium roughness of the surface layer of components must always match the specific hardness of the surface layer, ensuring uniform contact pressure.

Layers of treatment, deviations of macro-geometry of the surfaces (curvature, out-of-roundness, taper, etc.) provided by various technological methods have significant influence on the wear-resistance of components' surfaces.

New progressive technological methods need to be investigated and developed, which can be successfully used in production conditions to obtain surfaces having increased wear-resistance characteristics. Such methods may include rotary cutting, grinding with vibration damping, rotational honing, lapping with dosed removal of material of the surface layer, elastic rolling, etc. (Muratov & Muratov, 2007; Muratov & Gashev, 2014.

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