Studying the Tribological Properties of Parts Hardened by Rollers during Stabilization of the Operating Rolling Force

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Abstract—This article presents the results of experimental studies on the rolling of parts that are subject to wear and tear by rollers. The physical and mechanical properties and the microstructure of the surface layer of steel parts hardened by rollers were studied. The wear resistance characteristics of the specimens treated by rollers were obtained. A method and technology for rolling the parts and a device for the implementation of the method were developed.

Keywords: plastic surface deformation, rolling using rollers, stabilization of the force, friction distance, microstructure, wear resistance

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INTRODUCTION

When steel parts of machines, equipment, and structural components are used, their failure starts in most cases on the friction surface as a result of wear, fatigue, or contact interactions [1]. Therefore, the reliability and durability of products depend in many cases on the quality, strength, and stress–strain state of the metal of the surface layers of parts. Contact stresses and deformations are the main factors that determine the character and intensity of the wear of machine parts [2]. By controlling the properties of the surface layer by rolling it using rollers, one can enhance the wear resistance of friction pairs, thus increasing the longevity of steel parts [3].

A treatment based on plastic deformation of a thin surface layer, in particular, rolling using rollers, is considered to have a number of advantages over turning, grinding, polishing, and finishing. These advantages include the ease of operation and lack of the need for special-purpose equipment and large material and energy resources [4]. However, a number of questions that concern the technological processes of rolling during stabilization of the operating force such as the choice of modes and the optimization of the tribotechnical rolling parameters have not been answered up to now. Furthermore, no tribological studies of the influence of rolling during contact interaction of the friction pairs have been conducted [5].

Therefore, studies of the influence of the properties of the surface layer during rolling during stabilization of the operating force on the tribological characteristics and their optimization in order to increase wear resistance and contact strength are a topical scientific and engineering task; their performance was the subject of this work.

The aim of this work was to study the influence of the technology of hardening the surface layers of friction assemblies on their wear resistance and contact strength.

MATERIALS AND METHODS

Using a device developed for hardening parts by rollers during stabilization of the operating force [6], a shaft manufactured of 40 grade steel according to GOST 1050–88 state standard (AISI 1040/1042 or UNS G10400/10420) 50 mm in diameter was rolled on a 1K62 thread cutting lathe (Fig. 1).

The shaft was fixed in the center of the machine using a driver chuck and a device for hardening by rollers during stabilization of the operating force was fixed in the tool holder of the machine. The shaft was symbolically divided into four zones (Fig. 2): the first zone of hardening rolling during grinding at a rolling force of 3 kN, the second zone was the zone during grinding, the third zone for finishing rolling during turning at a rolling force of 0.75 kN, and the fourth zone for hardening rolling during turning at a rolling force of 3 kN.

Upon treatment, the shaft was cut into numbered specimens 11 mm wide in which holes 16 mm in diameter were bored. Then, every specimen was ground at the end faces.

To examine the microhardness, two specimens were selected: specimen 11 was rolled at a force of 0.75 kN during turning and specimen 14 was rolled at a force of 3 kN during turning. The experimental spec-
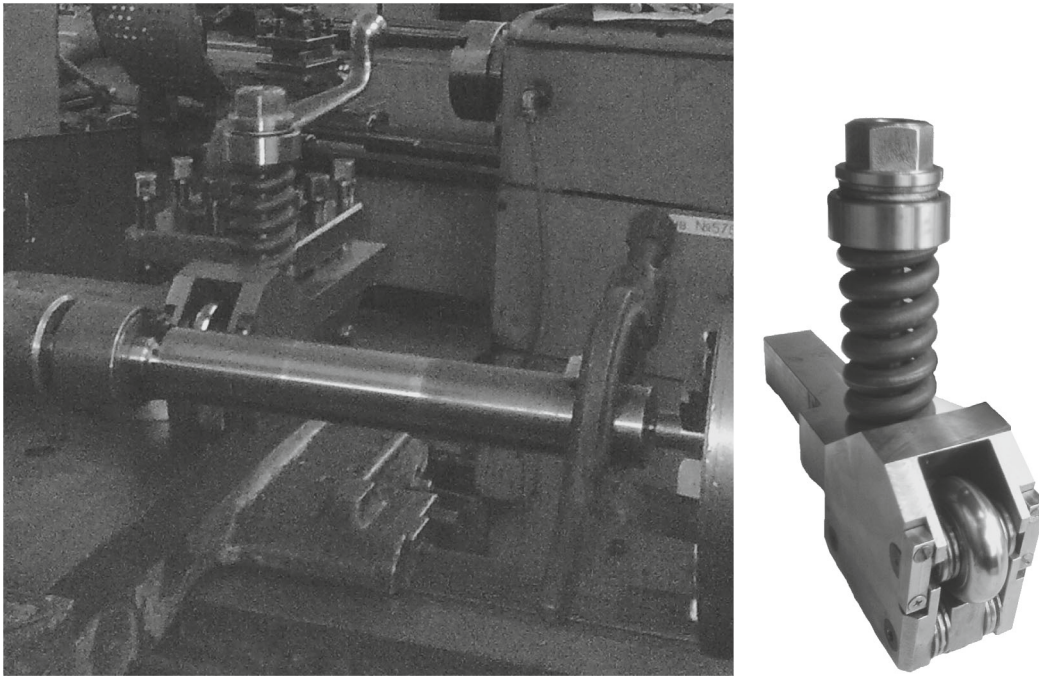
Fig. 1. The rolling of a shaft of 40 grade steel by a hardening roller during stabilization of the operating force.
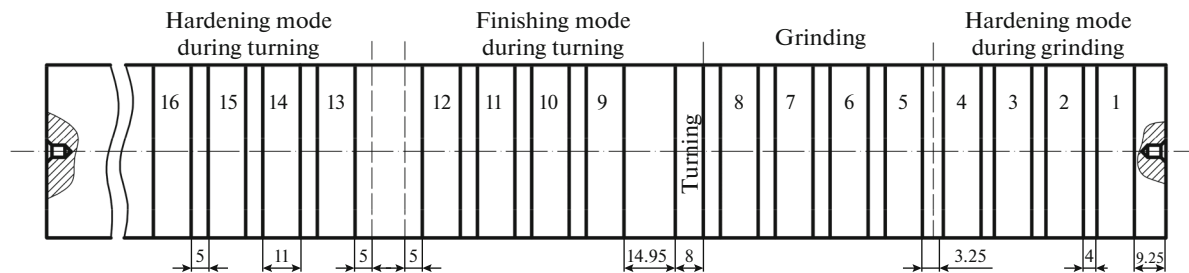

Fig. 2. The treatment zones of the shaft and markings of the experimental specimens.

imens were polished at the end faces with a diamond paste. Prior to polishing, the specimens were poured around the perimeter with the Protakril-M cold-curing plastic to prevent the rounding of the end faces during polishing.

The Vickers microhardness was measured using a PMT-3 device by AO LOMO, St. Petersburg, Russia along the radius of the roller every 0.2 mm at a load of 20 g. The microhardness was measured in three sections along the diameter of the specimen; in every section three imprints were made.

To conduct wear tests on the SMTs-2 friction test machine (NKII Instrument-Engineering Plant, USSR), specimens 50 mm in diameter were manufactured of 40 grade steel according to GOST 1050−88 state standard together with a specimen of Br. OTsS 8-21 tin-base bronze.

The steel specimens were treated according to four schemes, namely, (i) ground specimens with the surface roughness $R_a = 0.25$ μm; (ii) specimens rolled in the finishing mode at the force $P = 0.75$ kN during turning with the surface roughness $R_a = 0.15$ μm; (iii) specimens rolled in the hardening mode at $P = 3$ kN during grinding with the surface roughness $R_a = 0.12$ μm; and (iv) specimens rolled in the hardening mode at $P = 3$ kN during turning with the surface roughness $R_a = 0.17$ μm. The roughness of the surface of the inserts (bushings) during boring was $R_a = 0.36$ μm.

The friction pair was tested by the roller−conformal-surface scheme with a surface area of 264 mm^2 at a nominal unit load of 5 MPa and a circumferential speed of 79 m/min (Fig. 3). The specimens were copiously lubricated with Castrol Magnatec 10W-40 engine oil. The lubricant was fed into the friction area by the drop method.

When conducting the tests, the specimens were weighed every 1000 m of the friction distance using a VLR-200 analytical balance; prior to weighing, the specimens were degreased with alcohol and cooled. The tests were conducted for four friction pairs of each treatment variant.
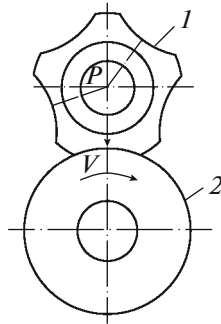
Fig. 3. The pattern of loading the experimental specimens: (*1*) bronze bushing and (*2*) steel shaft.

RESULTS AND DISCUSSION

Based on the measured microhardness values, graphs of changes in the microhardness through the depth were constructed (Figs. 4 and 5).

The depth of the hardened layer of specimen 14 rolled at a force of 3 kN during turning was 2–2.6 mm; the maximum microhardness at a depth of 180 μm from the surface was 30.7 MPa and the minimum microhardness at a depth of 2580 μm from the surface was 9.27 MPa. The depth of specimen 11 rolled at a force of 0.75 kN was 1−1.6 mm with the maximum microhardness at a depth of 180 μm from the surface of 28.8 MPa and the minimum microhardness at a depth of 2580 μm of 7.01 MPa.

The depth of the cold-work hardening was found by the Kheifets formula [4] as:

$$t = \sqrt{\frac{P}{2\sigma_y}},$$

where P is the rolling force and σ_y is the yield strength of steel.

To study the microstructure of the experimental specimens, they were etched with a 3% nitric acid solution. The microstructure of the specimens prior to rolling was similar (see Fig. 6a); it consisted of pearlitic and ferritic grains. Upon rolling during stabilization of the operating force, which was 3 kN, changes in the microstructure were observed in optical photomicrographs only on the surface layer of the experimental specimens rolled using a roller with a curvature radius of 6 mm (Fig. 6b). The changes consisted in a considerable extension of both ferritic and pearlitic grains in the circumferential direction of the rolling.

In the images of the surface layer (Fig. 6), pearlite has the form of alternating dark stripes; the lighter stripes are ferrite. The ferritic platelets have single dislocations at the ferrite−pearlite interface in some areas. When examining the microstructure of the layer nearer to the surface, an increase in the dislocation density in ferrite should be noted.

The examination of the microstructure of the specimens through the depth in the transverse section showed that the rolling of the shafts at a force of 3 kN by a toroid-shaped roller resulted in cold-work hardening of the surface layer through a depth of 3 mm.

Out of two structural components of steel, ferrite and pearlite, the softer ferrite is the first to experience plastic deformation. This leads to formation of a cellular structure in the grains of excess ferrite in which the dislocation density and grain micro-disorientation increase towards the surface of the shaft [7].

The dislocations in the ferritic interlayers in the pearlite occur at the ferrite−pearlite interface, which is consistent with the conclusion that the boundaries are the main source of dislocations.
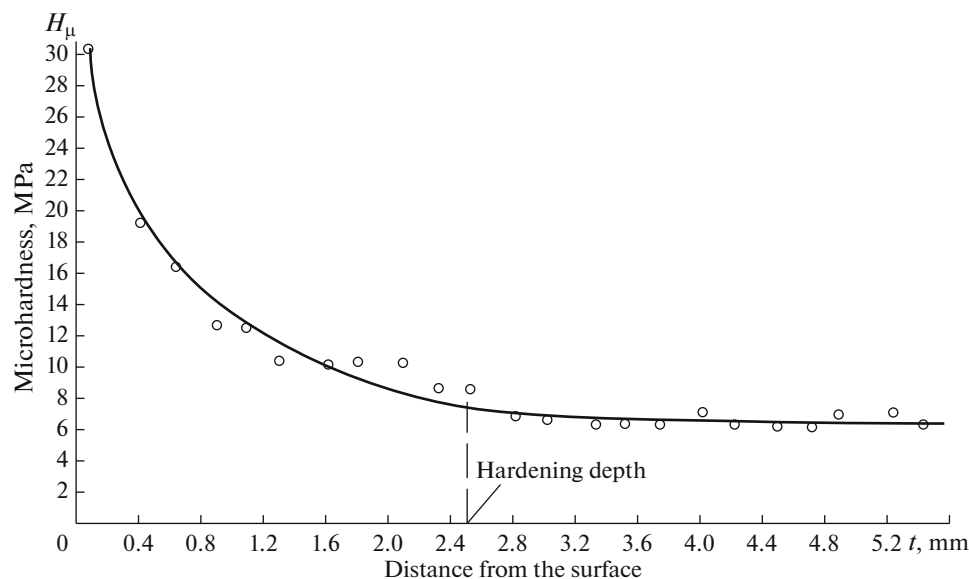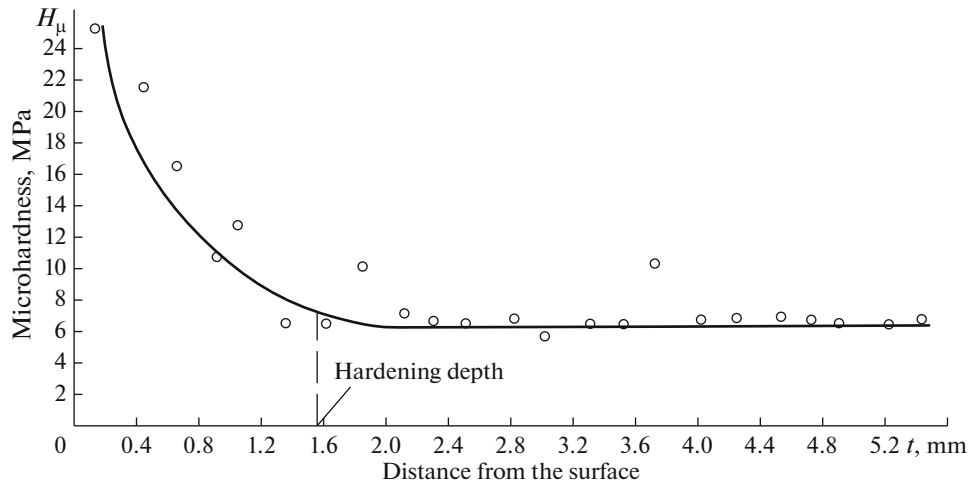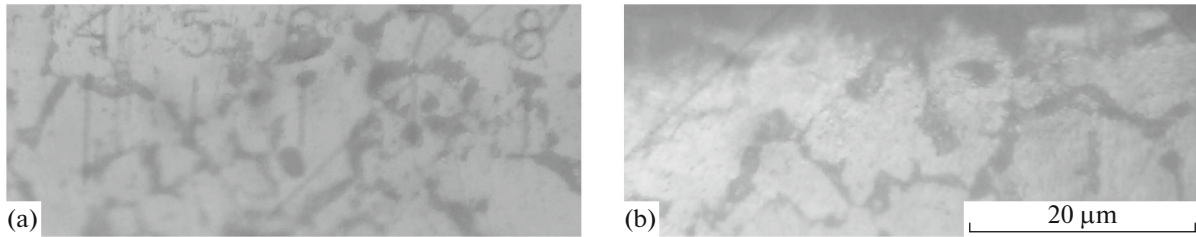

Fig. 4. The change in the microhardness through the depth of specimen 14 rolled in the hardening mode at a force of 3 kN during turning.

Fig. 5. The change in the microhardness through the depth of specimen 11 rolled in the finishing mode at a force of 0.75 kN during turning.


Fig. 6. The microstructure of the surface layers of experimental specimens of 40 grade steel: (a) prior to rolling and (b) during rolling at a force of 3 kN.

In Figs. 7 and 8, graphs of the wear of the bronze and steel specimens as functions of the friction distance are shown.

As can be seen from the graphs, at the moment of intensive break-in, $L = 20000$ m, a considerable increase in the wear of the bushing that operates in pair
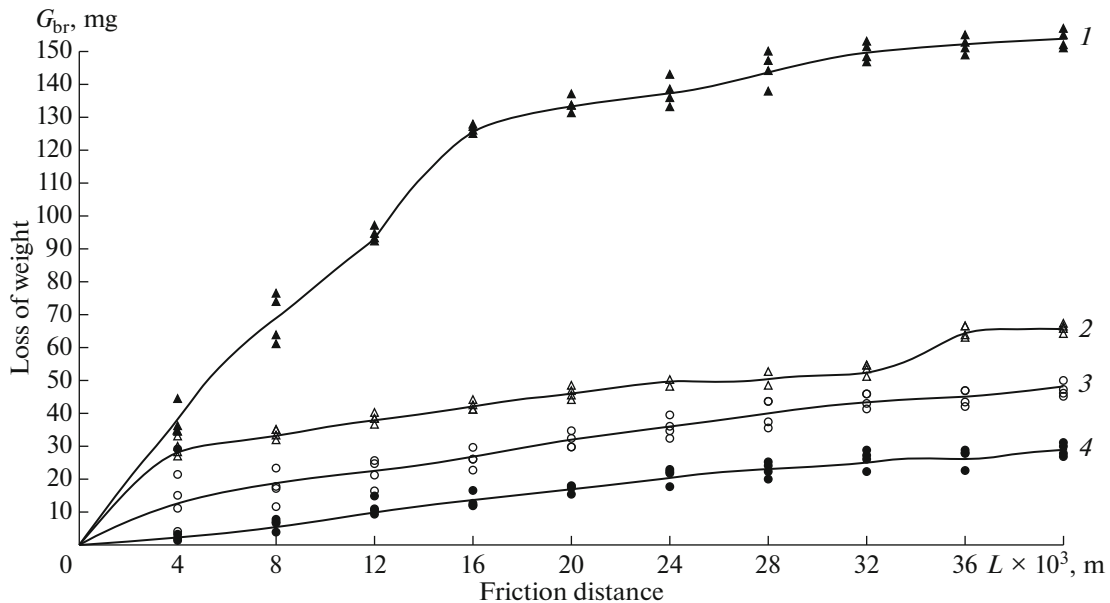
Fig. 7. A graph of the wear of bronze bushings: (*1*) bronze bushing in pair with the ground shaft; (*2*) bronze bushing in pair with the shaft rolled at 0.75 kN during turning; (*3*) bronze bushing in pair with the shaft rolled at 3 kN during grinding; and (*4*) bronze bushing in pair with the shaft rolled at 3 kN during turning.
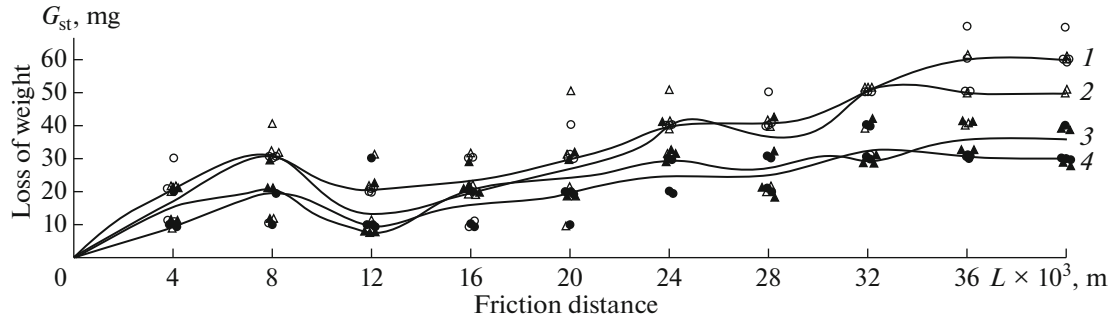
Fig. 8. A graph of the wear of 40 grade steel specimens: (*1*) ground steel specimen; (*2*) specimen rolled at 0.75 kN during turning; (*3*) specimen rolled at 3 kN during grinding; and (*4*) specimen rolled at 3 kN during turning.
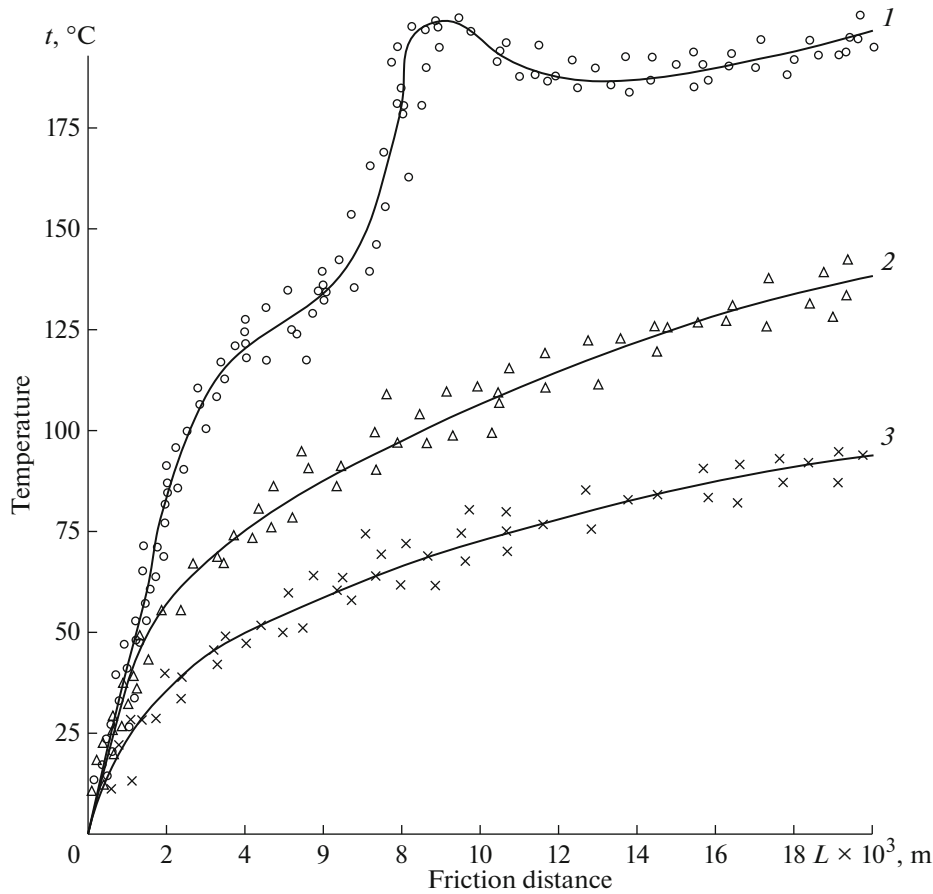
Fig. 9. The dependence of the temperature on the friction distance under different treatment conditions: (*1*) bronze bushing in pair with the ground shaft; (*2*) bronze bushing in pair with the shaft rolled at 0.75 kN during turning; and (*3*) bronze bushing in pair with the shaft rolled at 3 kN during turning.

with the ground shaft is observed. This results in an increase in the temperature of the experimental specimens compared with bushings that operate together with the shaft rolled at forces of 0.75 and 3 kN during turning and grinding. At the beginning of the tests, the friction coefficient *f* was 0.127 for the ground specimens while for the specimens rolled at the force *P* = 0.75 kN and *P* = 3 kN during turning and grinding, it

was 0.047 and 0.12, respectively. Subsequently, the friction coefficient reached the minimum (*f* = 0.016) for the specimens rolled at *P* = 3 kN during turning. As can be seen from Figs. 7 and 8, the break-in of the bronze bushings in pairs with the rolled steel specimens occurs several times faster than that of the ground specimens; the wear of the ground specimens over a considerable operation period exceeds that of

Table 1. The surfaces roughness parameters of the experimental specimens

Specimen	R_a, mm	n^*	H_{max}^*, µm	H_{min}^*, µm	t_p^*, %
Steel specimens					
At a friction distance of 20 000 m					
Specimen rolled at a force of 3 kN during grinding	0.28—0.29	5—7	5.3	6.79	91.1
Ground specimen	0.44—0.45	6—8	7.4	8.1	55
Specimen rolled at a force of 0.75 kN during turning (finishing mode)	0.16—0.20	3—4	4.8	3.2	95
Specimen rolled at a force of 3 kN during turning (hardening mode)	0.18—0.25	5—6	4.7	2.5	97
Upon a friction distance of 40 000 m					
Specimen rolled at a force of 3 kN during grinding	0.20—0.21	5—7	5.3	1.9	94
Ground specimen	0.27—0.28	10—11	7.9	4.85	54
Specimen rolled at a force of 0.75 kN during turning (finishing mode)	0.16—0.21	1—3	2.3	8.1	96
Specimen rolled at a force of 3 kN during turning (hardening mode)	0.17—0.22	3—4	2.8	1.3	97.5
Bronze specimens					
At a friction distance of 20 000 m					
Bushing in a pair with the specimen rolled at a force of 3 kN during grinding	0.20—0.24	11—13	4.96	6.78	82
Bushing in a pair with the ground specimen	0.61—0.62	12—16	6.76	7.73	51
Bushing in a pair with the specimen rolled at a force of 0.75 kN during turning (finishing mode)	0.21—0.22	9	4.81	2.46	95
Bushing in a pair with the specimen rolled at a force of 3 kN during turning (hardening mode)	0.18—0.20	9	4.85	2.10	95
Upon a friction distance of 40 000 m					
Bushing in a pair with the specimen rolled at a force of 3 kN during grinding	0.20—0.22	8	5.48	1.64	82
Bushing in a pair with the ground specimen	0.58—0.60	11	6.85	4.65	51.6
Bushing in a pair with the specimen rolled at a force of 0.75 kN during turning (finishing mode)	0.18—0.19	9	1.14	7.62	95
Bushing in a pair with the specimen rolled at a force of 3 kN during turning (hardening mode)	0.16—0.18	9	1.04	0.88	95.4

* n is the number of the roughness spacings within the distance; $^*H_{max}$ is the height of the highest profile peak; $^*H_{min}$ is the depth of the deepest profile valley; and $^*t_p$ is the relative profile bearing length.

the rolled specimens by 3—3.5 times in this case. The specimens rolled at the force $P = 3$ kN during turning exhibited the minimum wear; this is explained by not only the hardening effect and the increased strength but also the optimal roughness and improved lubrication conditions due to formation of oil pockets in which the lubricant is retained if the specimens treated by this technique.

Alongside the measurements of the wear resistance [8], the temperature in the friction area was measured (Fig. 9). Analysis of the test results showed a considerable increase in the temperature for the bronze specimen that operated in pair with the ground shaft and rubbings and scores on the friction surface [8].

In pairs 2—3 with the specimens rolled in the finishing and hardening modes during turning, the temperature changed smoothly without any jumps and no scores were observed on the friction surfaces. For the rolled specimens, the dependence of the temperature t on the friction distance L was established.

For the pair consisting of a bronze bushing and a steel shaft rolled in the finishing mode at the force $P = 0.75$ kN, the dependence is expressed by the equation $t = 2.685L^{0.39}$; the corresponding equation for the bronze bushing in pair with a steel shaft rolled in the hardening mode is $t = 1.702L^{0.39}$.

A new relief was formed on the surface of the bushings for all specimens. In Table 1, the roughness parameters of the steel and bronze specimens are presented after covering friction distances of 20 000 and 40 000 m, respectively.

It can be seen from Table 1 that the profile bearing length t_p increases in the rolled specimens as a result of the reduced roughness of the surface and in the course of the break-in in pairs with the bronze bushings, a new relief is formed.

The area of the bearing surface of the rolled specimens is 1.5−2 times larger in the upper layers and 1.1−1.2 times larger in the lower layers than that of the ground specimens. The height of irregularities on the rolled surface decreased by 1.5−1.8 times and that on the ground surface decreased by 1.2 times. The surface roughness of the rolled samples resulting from the wear of the latter is formed predominantly as a result of abrasion of the protrusion peaks without considerable changes in the roughness in its lower sections [10]. As a result, the difference in the area of the bearing surface between the ground and rolled surfaces increased in the course of the wear even more.

CONCLUSIONS

Studies of the wear resistance of parts hardened by rollers during stabilization of the operating rolling force have shown that during hardening rolling of shafts by a toroid-shaped roller at a rolling force of 3 kN, the wear resistance of bronze bushings is three times higher than that when the bushings operate in pairs with ground shafts. Studies of the surface roughness of the specimens rolled in the hardening mode have shown that during turning a considerable reduction in the surface roughness and an increase in the area of the bearing surface are observed and a surface that is favorable for formation of oil pockets is shaped on the bushings, which, in turn, reduces the friction coefficient and the temperature loading on the friction pair during operation.

The technique for treating parts by rollers during stabilization of the rolling force allows the production of hardened layers of different thicknesses with a sufficiently high and uniform hardness and increases the wear resistance of the friction pairs.

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