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Research article

Increase of Wear and Heat Resistance of the AISI 304 Steel Surface Layer by Multi-Pass Nanostructuring Burnishing

Viktor P. Kuznetsov[a,*], Anna V. Kosareva[a]

[a]*Ural Federal University, Ekaterinburg, Russia.*

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* Corresponding author:

Viktor P. Kuznetsov
E-mail: wpkuzn@mail.ru

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A B S T R A C T

The paper presents the results of experimental studies of the AISI 304 steel disc surface after finishing turning, electropolishing and nanostructuring burnishing after one and five passes of the tool with a natural diamond tip with a radius of 2 mm. It is shown that surface layer nanocrystallization provides for almost complete decomposition of austenite in a layer up to 100 μm thick, an increase in microhardness up to 400...450 HV0.025 and a 3.3-fold reduction in the wear intensity on hardened AISI 1045 steel under conditions of lubrication with industrial oil compared with electropolishing. The content of residual austenite in the surface layer is not more than 5% when the temperature rises to 400°C.

1. INTRODUCTION

The present-day parts of tribo-couplings should ensure reliable performance of machines and mechanisms in long-term operation, including in such extreme conditions as increased loads, speeds, temperatures, presence of abrasive and aggressive media. Therefore, increased requirements for wear resistance, ability to resist deformations under contact loads, heat resistance, corrosion resistance are imposed on friction unit materials of critical duty. To the greatest extent, an increase in operational properties should be provided by the surface layer of materials.

Austenitic chromium-nickel steels, due to their high corrosion resistance and manufacturability, are widely used in the oil and gas, chemical, food and other industries. However, their significant disadvantage is low stress-strain properties, which are not improved by heat treatment. An increase in the strength characteristics of thermally non–hardened steels can be achieved by reducing their grain size (grain boundary hardening), as well as formation of various dislocation structures inside grain substructures (substructural hardening).

For example, in [1] it was shown that the hardness of AISI 304 stainless austenitic steel, annealed at 1050°C followed by water quenching, largely depends on the grain size. The presence of deformation twins in the structure increases the strength characteristics of steel.

The possibility of increasing yield and ultimate stress of austenitic stainless steel by equal channel angular pressing (ECAP) using the example of AISI 304 steel is considered in [2]. After eighth-pass ECAP in a matrix with an inclination angle of 105° at a temperature of 350°C, three types of grain structure were observed in the steel structure: (a) short elongated grains/subgrains with an average width of 71 nm formed in the regions of shear bands, (b) a mixture of large (200-350 nm in size) and nanocrystalline (15-70 nm) equiaxial grains developed outside the shear bands, and (c) nano-twin lamellae of 3-20 nm width inside nanocrystalline grains. It should be noted that the changes in the structure of the treated samples correlated with their mechanical properties determined by tensile tests and microhardness measurements. For example, the yield point of the alloy reached a value of 1498 MPa, which is about 3.5 times higher than the initial value. At the same time, moderate ductility was maintained.

In [3], the changes in the microstructure, mechanical properties and corrosion behavior of AISI 304 austenitic stainless steel treated with a pseudospark pulsed electron beam (PSPEB) with a different number of pulses were investigated. The results of the EDS analysis showed that the precipitated ferritic phase was dissolved in the matrix, forming a homogeneous composition in the modified layer. The observation of the microstructure showed that the homogeneous submicron grains with slip bands in different directions were distributed in the modified layer, completely replacing the original large grains more than 10 microns after 5,000 pulse treatment. The microhardness of AISI 304 stainless steel increased with an increase in the number of pulses, which is mainly due to grain refinement and plastic deformation strengthening.

The wear resistance of precision workpieces, along with the structural and phase state of the material, is also determined by the quality of the surface. Hardening and roughness burnishing of the AISI 30455 austenitic steel by diamond burnishing was investigated in the work of J. Maximov et al. [4]. The sample burnishing after quenching by heating up to 1100°C and cooling with water provided a roughness of Ra = 0.1 μm. The maximum microhardness of the surface 677 HV was obtained after hardening and subsequent heating at 350°C for 3 hours. The relief of residual stresses caused by burnishing and partial martensitic transformation α' were observed.

In [5], a method for surface layer processing by ultrasonic rolling treatment with a vibration frequency of 20 kHz is proposed. It was found that after four passes, the hardened layer with a thickness of 600 μm and a gradient layer with a nanostructure up to 30 μm thick are formed. This made it possible to increase the hardness 2 times more compared to the original material. Compared with turning, the roughness of Ra decreased by 20 times from 3.92 μm to 0.19 μm.

The primary problem is to create and improve the methods for finishing surface layer treatment of precision workpieces of tribo-couplings, providing hardening and high topographic properties of the surface layer. An effective method of finishing structural steels is the technology of nanostructuring burnishing, which makes it possible to form the nanostructured state and sub-microrelief of the surface layer during the precision workpiece serial manufacture at metalworking centers [6-8].

2. STRUCTURE AND PROPERTIES OF THE AISI 304 STEEL SURFACE LAYER AFTER NANOSTRUCTURING BURNISHING

Nanostructuring burnishing of the samples from AISI 304 austenitic stainless steel of industrial smelting containing Fe and in % vol.: 0.06 C; 17.61 Cr; 8.56 Ni; 0.29 Ti; 0.89 Mn; 0.46 Si; 0.22 Mo; 0.14 Co; 0.24 Cu; 0.017 P; 0.019 S was carried out on the disc-type parts with a diameter of 70 and 12 mm thick. After quenching from 1050°C in water, the structure of the hardened steel appeared to be an austenitic matrix (Figure 1). The hardness of the samples was HB 156.

The flat surfaces of the disks were previously subjected to finishing turning and, afterwards, to nanostructuring burnishing on the MULTUS B300 turning and milling center. Finishing turning with an allowance of 0.1 mm was carried out with a Sandvik WNGA 080404 carbide plate with a radius at the top of 0.4 mm at a speed of 80 m/min, a feed of 0.06 mm/rev using Rhenus cooling lubricant (FRG).

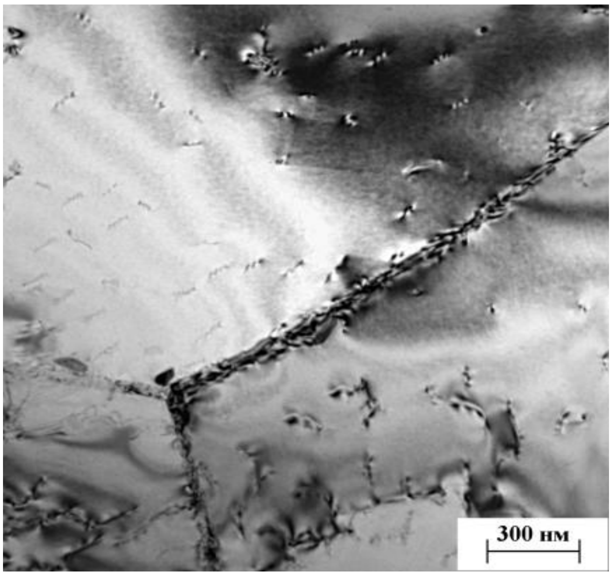


Fig. 1. The structure of the AISI 304 steel surface layer in its original state

Further, with one set-up of the workpiece, nanostructuring burnishing was carried out at a speed of $v_b = 50$ m/min, a feed of $f_b = 0.01$ mm/rev, a load of $F_b = 200$ N using the same cooling lubricant for one and five tool passes (Figure 2). The working part of the indenter made of natural diamond had a spherical sharpening with a radius of $R = 2$ mm.

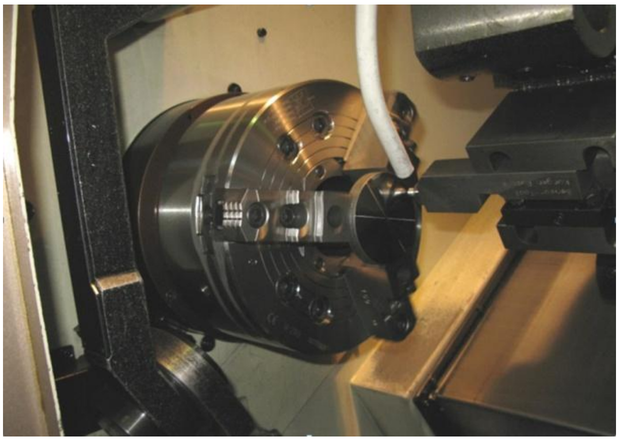
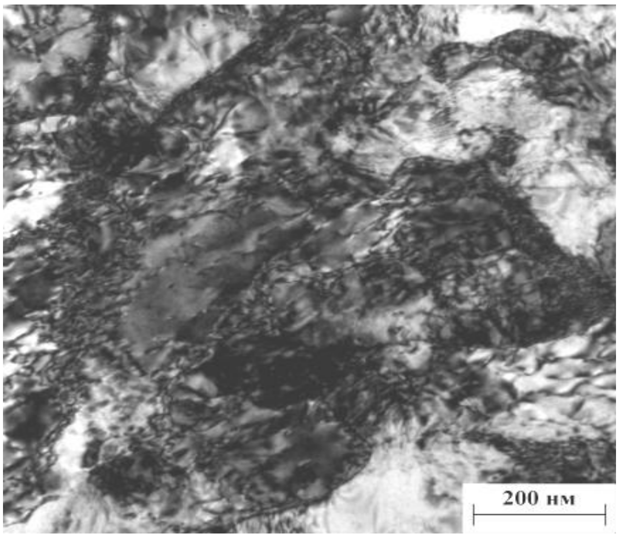


Fig. 2. Nanostructuring burnishing of an AISI 304 steel disc on MULTUS B300 machine.

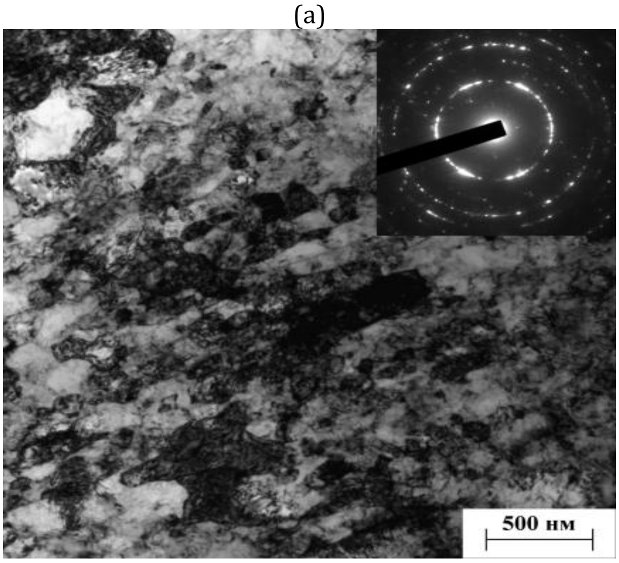
The purpose of this work is to study the tribological properties and heat resistance of AISI 304 steel after finishing with a multi-pass nanostructuring burnishing by a sliding indenter on a turning and milling center.

2.1 Investigation of the structural and phase composition of the AISI 304 steel surface layer after nanostructuring burnishing

Electron transmission microscopy shows that in the process of nanostructuring burnishing, a deformation martensite fragmented structure appears in a thin surface layer of hardened AISI 304 steel, in which submicro- (Figure 3, a) and nanoscale crystallites are simultaneously present (Figure 3, b).



(a)



(b)

Fig. 3. The structure of the AISI 304 steel surface layer after nanostructuring burnishing with grains of submicro- (a) and nanosize (b).

The results of X-ray phase and structural analysis of the surfaces after finishing turning, single-pass and multi-pass nanostructuring burnishing show that multi-pass nanostructuring burnishing of AISI 304 steel has the greatest effect on the γ-phase (austenite) content in the surface layer, the amount of which in the initial structure of the hardened steel is more than 95 % vol., after finishing turning and single-pass burnishing – 90 %, after multi-pass nanostructuring burnishing, the proportion of residual austenite does not exceed 5% (Table 1).

The results given in Table 1 also show that the integral width of the X-ray line (111) γ increases from 10 min (for austenite of the initial hardened steel) to 36 min after finishing turning and single-pass burnishing. This reflects an increase in the density of dislocations in austenite and micro-distortions of its crystalline FCC lattice.

Table 1. The results of X-ray phase analysis of the AISI 304 steel sample surface after nanostructuring burnishing.

Sample state	γ, vol.%	$B_{(111)\gamma}$, min	$B_{(110)\alpha}$, min
Initial (electropolishing)	≥95	10	–
Finishing turning	90	36	59
Single-pass burnishing ($n_p = 1$)	90	36	33
Nanostructuring burnishing ($n_p = 5$)	≤5	–	37

Maximum integral width of the α-phase X-ray line $B_{(110)\alpha} = 59$ min is fixed in a thin surface layer after finishing turning, when in the structure, there is 10 % vol. of α-phase consisting of deformation martensite and δ-ferrite deformed by turning. After five burnishing passes ($n_p = 5$), the width of the α-phase line takes values $B_{(110)\alpha}$ = 33...37 min.

Figure 4 shows the change in the content of the γ-phase (austenite) in the depth of the surface layer *h*, obtained by successive electrolytic removal of metal from the workpiece surface.

It follows from the graphs that the multi-pass nanostructuring burnishing of AISI 304 steel leads to almost complete deformation decay of austenite in a layer up to 100 μm thick.

The formed surface layer is characterized by the increased values of microhardness $HV_{0,025}$ compared to the initial state and single-pass burnishing to a depth $h \approx 200$ μm (Figure 5).

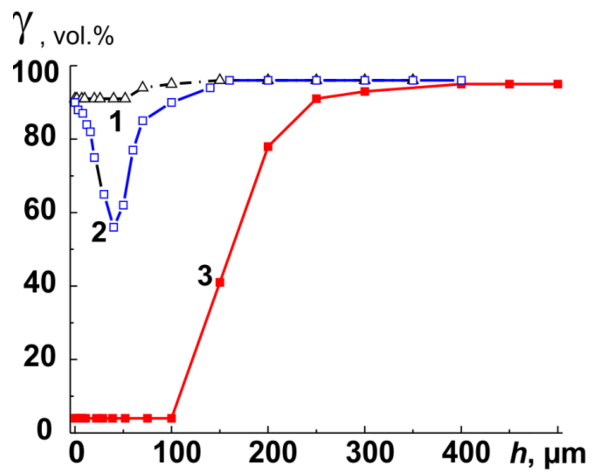


Fig. 4. The change in the content of residual austenite in the depth h of the AISI 304 steel surface layer: 1 – turning, 2 – single–pass burnishing, 3 - nanostructuring burnishing ($n_p = 5$).

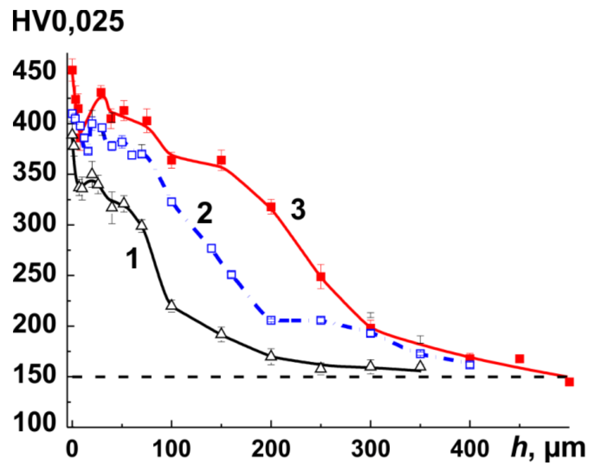


Fig. 5. The change of microhardness in depth *h* of the AISI 304 steel surface layer: 1 – turning, 2 – single-pass burnishing, 3 – nanostructuring burnishing ($n_p = 5$).

2.2 Increase in wear and heat resistance of the austenitic steel AISI 304 surface layer by multi-pass nanostructuring burnishing

The effect of nanostructuring burnishing on the performance properties of the surface layer of AISI 304 hardened austenitic stainless steel was studied under conditions of sliding friction on a counterbody in the form of a plane made of AISI 1045 steel at hardness HRC 50 with lubrication (Industrial oil). The tribological tests were carried out at the reciprocating motion unit at the Institute of Engineering Sciences (Russian

Academy of Sciences, Ural Branch, Yekaterinburg). The test scheme is shown in Figure 6.

The wear intensity was determined by the formula

$$Ih = \frac{Q}{\rho Sl}, . \quad (1)$$

where Q is sample mass loss, g; ρ is sample material density, g/cm^3; S is a geometric contact area, cm^2.

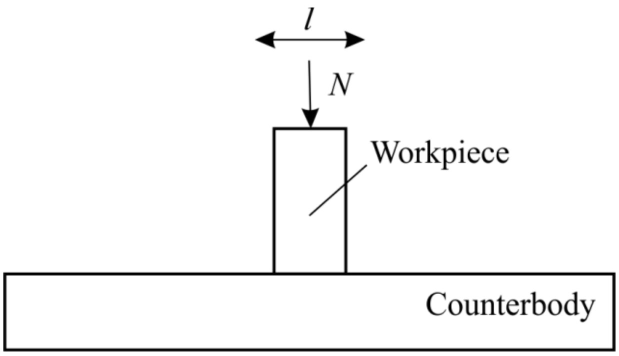


Fig. 6. The wear resistance test scheme: N – normal load; l – stroke value.

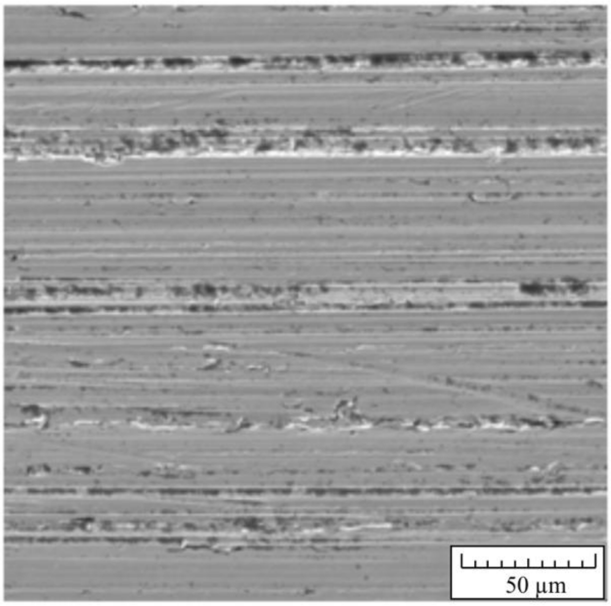
During the tests, the friction force F_μ was continuously recorded, it was measured using an elastic element – a spring (ring) with resistance strain gauges glued to it. Spring calibration was performed using gaged loads (Figure 7).

Fig, 7. Spring calibration using gaged loads,

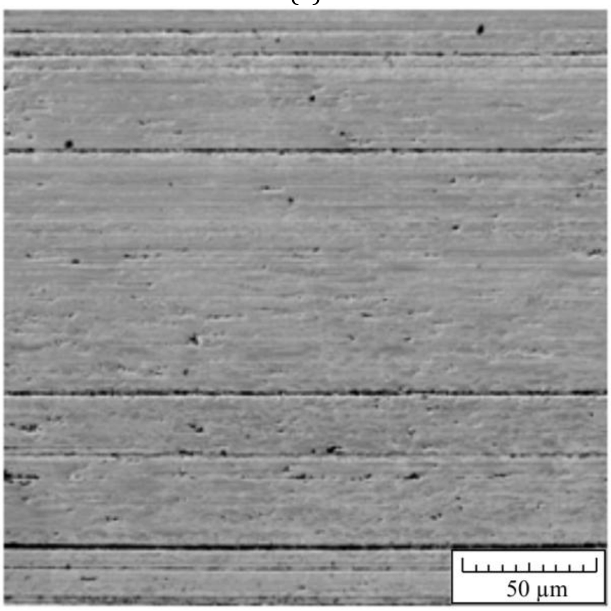
The registration of the strain gauge signal and result processing were carried out on a computer using special software. The coefficient of friction μ was defined as the ratio of the friction force F_μ to the normal load N. The test results are given in Table 2.

Table 2. Wear rate and coefficient of friction

Sample state	n_p	Ih,10-9	μ
Initial (electropolishing)	-	8.3	0.1
Single-pass burnishing	1	1.7	0.08
Nanostructuring burnishing	5	2.5	0.05



(a)



(b)

Fig. 8. The wear surfaces of hardened AISI 304 steel samples during tests on a AISI 1045 steel plate with lubrication after electropolishing (a) and nanostructuring burnishing (b).

From the above data, it follows that the minimum values of wear intensity Ih = 1.7 is provided by a single-pass burnishing. An increase in the number of tool passes up to n_p = 5 gives a slight increase in wear intensity up to the value of Ih = 2.5, while in comparison with the initial undeformed state, a decrease by 3.3 times in wear intensity is observed.

Figure 8 shows the results of a scanning electron microscope study of the wear surfaces of samples made of AISI 304 corrosion-resistant steel after sliding friction tests with lubrication on a 45 carbon steel plate.

Figure 8b shows that nanostructuring burnishing localizes the development of plastic displacement on the AISI 304 steel surface affected by friction during the tests on AISI 1045 steel. On the friction surfaces of the steel subjected to multi-pass burnishing, elastic displacement prevails, characterized mainly by smooth surface formation. As follows from Table 2, due to multi-pass burnishing, there is a decrease in the coefficient of friction of AISI 304 steel paired with 45 carbon steel under lubrication conditions.

To study the heat resistance of the AISI 304 steel surface layers formed by multi-pass nanostructuring burnishing, the samples were subjected to vacuum tempering (annealing) lasting 2 hours with a sequential temperature increase after 50°C in the temperature range 100 ...900°C.

It is established that the content of residual austenite in the AISI 304 steel surface layer treated with nanostructuring burnishing remains at the level of ~5% when heated to 400°C (Figure 9).

With an increase in the tempering temperature above 400°C due to the inverse α→γ-transformation, the amount of deformation martensite on the burnished surface decreases, and the amount of austenite, respectively, increases, reaching 95 % vol. at a tempering temperature of 700°C.

However, in the temperature range from 150 to 550°C, there is a gradual decrease in the integral width of the X-ray lines (110)α and (111)γ reflecting a decrease in defects and micro-distortions of the deformed austenite crystal lattice (Figure 10).

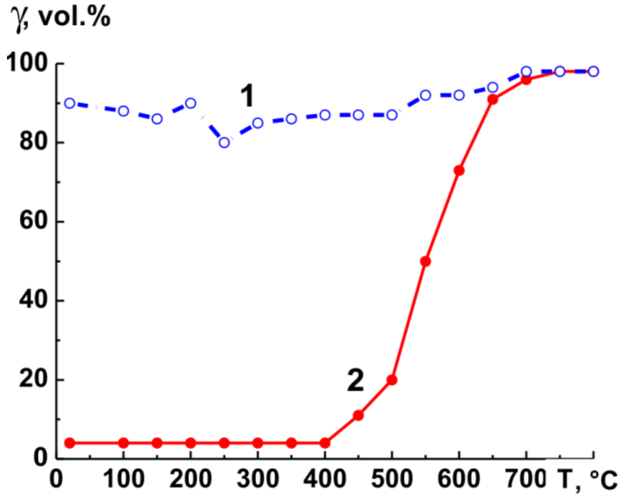


Fig. 9. The effect of tempering temperature on the residual austenite content in the AISI 304 steel surface layer after single-pass (1) and multi-pass (2) nanostructuring burnishing.

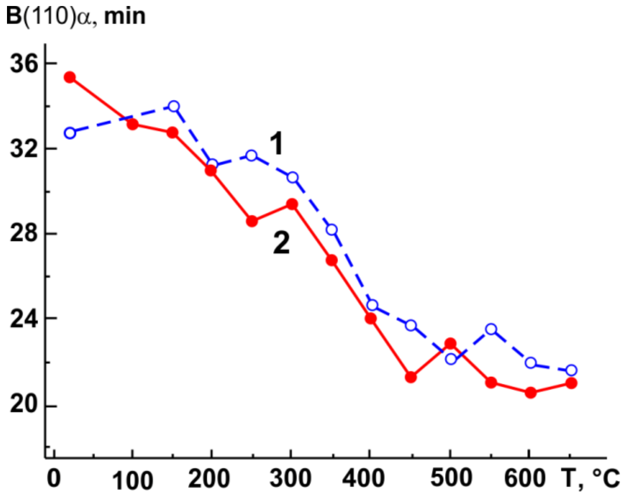


Fig. 10. The effect of tempering temperature on the integral width of the X-ray line B(110)α in the AISI 304 steel surface layer after single-pass (1) and multi-pass (2) nanostructuring burnishing.

3. CONCLUSION

This study established the effect of multi-pass nanostructuring burnishing on the properties of the AISI 304 austenitic stainless-steel surface layer hardened at 1050°C, on heat and wear resistance increase under sliding friction conditions on a plate made of AISI 1045 steel with a hardness of HRC 50 using industrial oil lubrication. Nanostructuring burnishing was carried out after finishing turning using a tool with a natural diamond tip with a radius of 2 mm at a speed of 50 m/min, a feed of 0.01 mm/rev and a load of 200 N using coolant. The

X-ray phase analysis showed that after five passes of nanostructuring burnishing of AISI 304 steel, almost complete deformation decay of austenite occurs in a layer up to 100 μm thick. As a result, the surface layer has a microhardness of 400...450 $HV_{0.025}$. The roughness of the surface layer after five tool passes was Ra = 0.13 μm. It was found that, compared with the surface condition of AISI 304 steel after electropolishing (microhardness 225 $HV_{0.025}$), nanostructuring burnishing provides a 3.3-fold reduction in wear intensity. On the friction surface of the hardened steel, after finishing turning and electropolishing, the processes of plastic metal displacement are significantly developed. Nanostructuring burnishing localizes the development of plastic displacement, and elastic displacement is predominant. As a result of surface nanostructuring, the coefficient of friction of AISI 304 steel over AISI 1045 steel under lubrication conditions decreases from 0.1 to 0.05. To study the heat resistance of the nanostructured layer, the samples were made that were subjected to vacuum tempering for duration of 2 hours with a sequential temperature increase after 50°C in the temperature range of 100 ...900°C. It was found that when the samples were heated to 400°C, the content of residual austenite in the surface layer did not exceed 5%.

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