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NANOINDENTATION AND ATOMIC FORCE MICROSCOPY OF THIN SURFACE LAYERS FORMED ON THE SHAFT SURFACE AFTER BURNISHING PROCESS

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Abstract

The article presents the experimental results of investigation of the pumps shaft surface made of stainless steel after burnishing process. The process of burnishing shafts proposed here aims at increasing the service durability of marine pump shafts of seawater installations, which should give economic benefits in comparison with traditional methods. Burnishing process enables the achievement of high smoothness of machined surface together with the surface layer hardening. This process has been performed in industrial experience on universal machine tools and on CNC machines but it is regarded as plastic tooling. Therefore, the final formation of dimensions and service properties with the use of burnishing constitutes a chipless and dustless treatment, which allows for ranking burnishing among ecological tooling methods.

The properties of the surface layers determine the tribological properties of the shaft. The methods of scanning electron microscopy (SEM), atomic force microscopy (AFM) and nanoindentation (NI) were used. The morphology of the changed layers formed by plastic deforming of steel during burnishing treatment was investigated on micro- and nanolevel by SEM and AFM after 1, 2, 3 and 4 passed of burnishing tool. The values of microhardness and Young's modulus were measured on the shaft cross section from the surface till the 50 – 300 µm depth. The presence of the soft changed layer on the hardened shaft surface after burnishing process determines the decrease of the coefficient of friction during exploitation.

Keywords: *microstructure, atomic force microscopy, nanoindentation, microhardness, Young's modulus, burnishing process*

1. Introduction

Many scientific centres all over the world deal with burnishing treatment. Research programs usually cover issues related to burnishing of cast iron, some heat resisting alloys, stainless steel, copper and aluminium alloys, titanium and its alloys, composite and intermetallic coatings as well as parts produced by sintering metal powders. Burnishing is an effective and widespread method to improve the properties of the machine parts [4]. Roller burnishing based on microplastic forming of surface layers [1, 3, 6]. This work direct to experimental research of the morphology and properties of surface layers with high-resolution methods SEM, AFM and NI on micro- and nanolevel. Very often, the attention of researcher of burnishing process is directed only on roughness of the surface and hardening effect after treatment. In this work, the results of microplastic forming are observed on microlevel.

2. Samples preparation

The burnishing process of shaft pins ϕ 40 mm in diameter, made of X5CrNi18-10 stainless steel was carried out on a universal CDS 6250 BX-1000 centre lathe. The preliminary lathing process was conducted by a cutting tool with WNMG 080408 WF removable plates by Sandvik Coromant. The process of burnishing was conducted by SRMD one roller burnish by Yamato. During the burnishing process, the following machining parameters were used: burnishing force 1.1 kN, burnishing speed 35 m/min and feed 0.13 mm/rev. All technological details are shown in [8, 9, 10].

3. Research methodology

The roughness investigation of burnished surfaces was made using contact profilometer Mitutoyo (Japan). The length of measured profile was 1.5 mm, the speed of probe moving was 0.25 mm/s, the number of profile points was 3000.

The measurements of microhardness were made on shaft cross section with two methods: with microhardness tester PMT-3 (Russia) and with NI Hysitron TI750L Ubi (USA). In the first the value of microhardness was calculated according to diagonal of restored stamp [5]. The last method named "Oliver -Pharr" is based on continuous implementation of the Bercovich tip with curvature radius about 150 nm into tested sample under acting of smoothly increasing loading with the subsequent unloading and registration of dependence «load – movement of the tip [11]. From these dependence «load – movement of the tip» it is enable to determine not only microhardness of the material but the elastic properties (Young modulus). Three stamps in one line parallel to the surface were made in both methods from the surface on the cross section into the material. Then an average value was calculated on different distance from the surface and the dependences "Depth from the surface – Microhardness" were constructed.

The morphology of burnished surfaces was investigated by SEM and AFM. Surface microstructure was investigated using the SEM «Mira» produced «Tescan» (Czech Republic). Topography investigation was provided on NT-206 AFM device (produced in Belarus) in contact regime using standard silicon cantilever with tip radius about 10 nm. The silicon cantilevers of CSC 38 type (Micromasch, Estonia) with stiffness coefficient k = 0.08 N/m were used in this cause. During AFM surface scanning two type of dates were written in two different files: a normal deflection of cantilever and a cantilever twist. The normal deflection forms the topography image. The lateral projection of cantilever twist forms image the lateral forces named "Torsion". The cantilever twist is caused by surface properties and it is more sensitive to the different phases in the surface than the topography regime. Two more method of AFM – measurement were applied in this work: determination of adhesion forces between AFM-tip and thin changed layer on the surface of burnished shaft according to the unloading curves [10] and determination of Young modulus of this layer according to loading curves [7]. Both methods use Force spectroscopy into surface by AFM –probe. The silicon cantilevers of NSC 11 type (Micromasch, Estonia) with stiffness coefficient k = 3 N/m were used for Force spectroscopy.

4. Results and discussion

The profiles of surfaces after burnishing processes obtained with profilometer are shown on Fig. 1. The Ra of surfaces after one pass is 128 nm. The second pass decreases the roughness till 98 nm. The third pass increase the relief till Ra 216 nm and the fourth again decrease relief till 130 nm. This non-monotonic roughness dependence from the passes of tool along the surface can be explained by creation of plastically changed layer. It forms during the first pass from plastically changed steel layers and machine oil used by burnishing. The second pass of tool smooths it and make more thinly. But the third pass involves the new volumes in the process of microplastic forming of material and the forth pass smooths them again. The deflections of asperity of surface are not homogeneous even for length of profile 1.5 mm. The asperities and the cavities in profiles are more symmetric and homogeneous after the second and the forth passes.

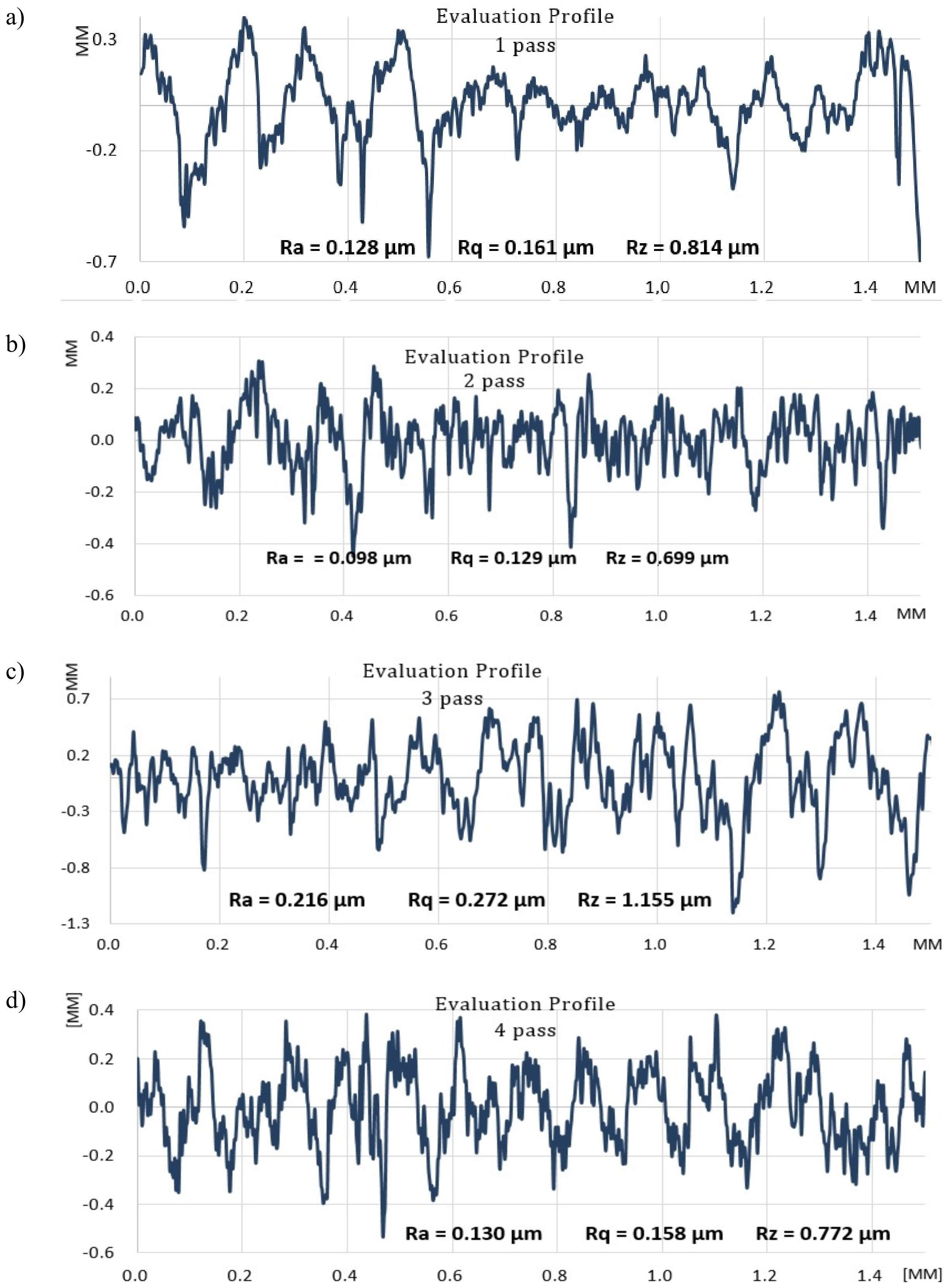

Fig. 1. The profiles of treated surfaces: (a) one pass, (b) two passes, (c) three passes, (d) four passes

Microhardness grows after different number of tool passes in burnishing process from pass to pass (Fig. 2). It increases as from the depth of shaft about 300 µm till the shaft surface so from pass to pass. The highest value about 7.5 GPa has the shaft near the surface after 4 passes of tool. However, the microhardness on the depth 300 µm is the similar for 3 and 4 passes. It is about 6 GPa.

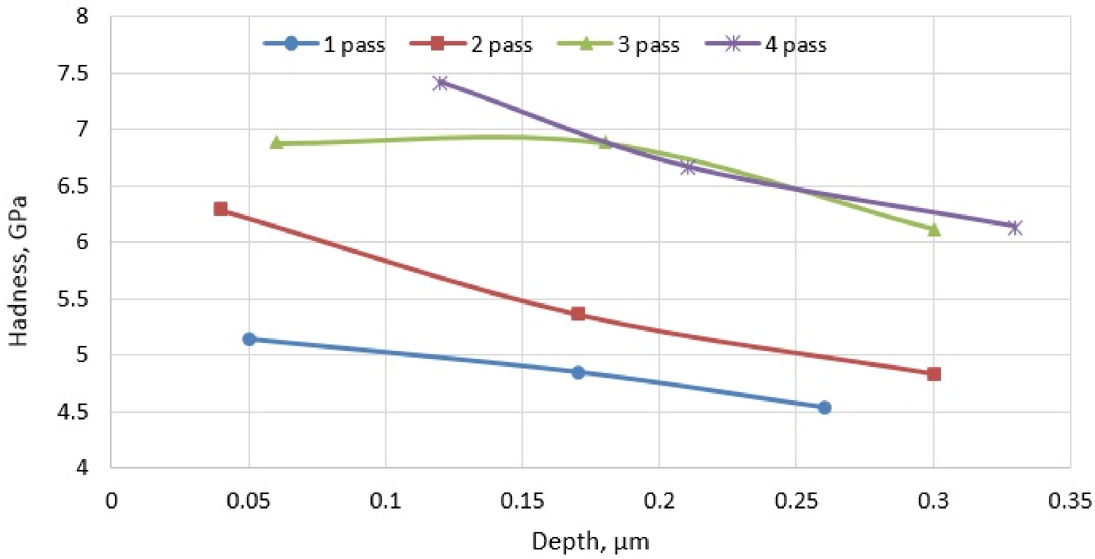

Fig. 2. The changes of microhardness of treated surfaces with different number of burnishing passes, obtained with microhardometer on the depth till 350 µm

NI enables to measure the properties of thinner layers – about 5 µm near to the surface (Fig. 3 and 4). It shows that 4 passes provide the highest level of microhardness on the surface so in the depth of material. The decrease of Young modulus values on the surface for all number of passes when the microhardness increases is remarkable (Fig. 4). This fact can be explained by the presence of softer layer on the surface. But the surface after 4 passes shows the essential increase of Young modulus just under the surface layer. When the sample after one pass has Young modulus 140 GPa under the surface and in the depth of materials about 160 µm, the sample after 4 passes achieves 210 GPa under the surface on the depth 20 µm.

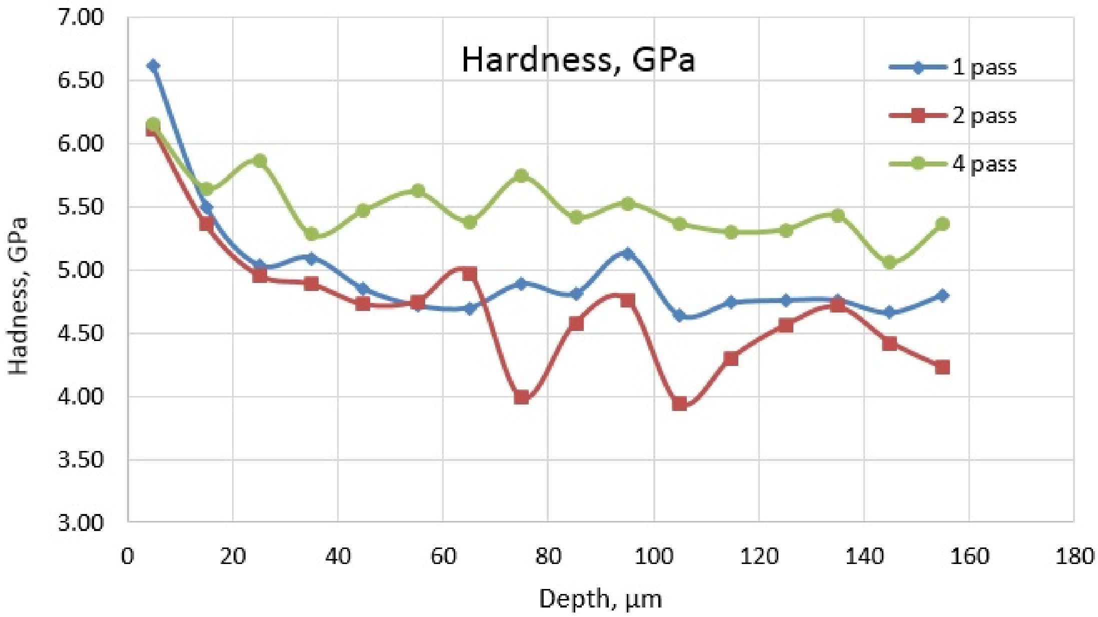

Fig. 3. The changes of microhardness of treated surfaces, obtained with NI on the depth till 160 µm

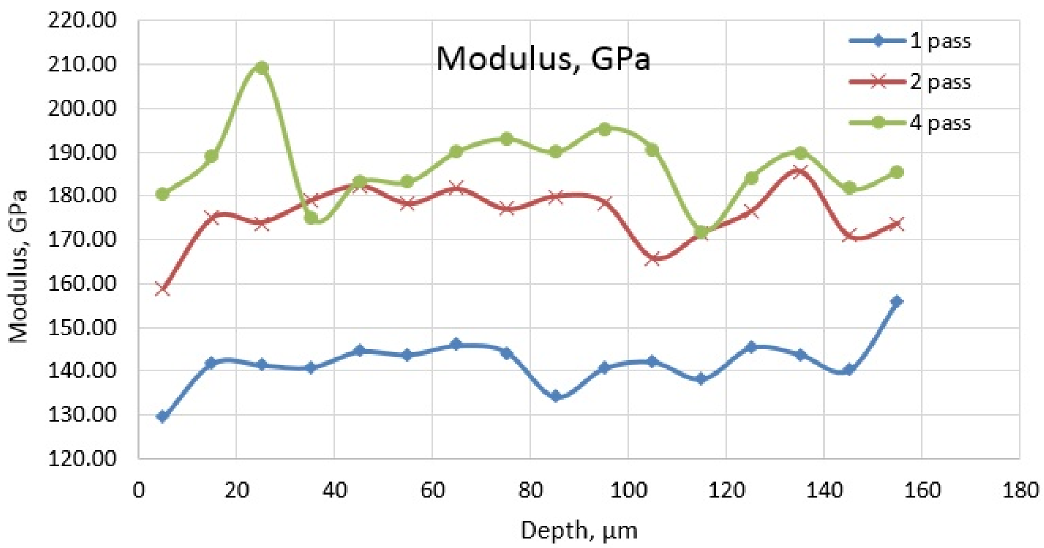

Fig. 4. The changes of Young modulus of treated surfaces, obtained with NI on the depth till 160 µm

The presence of a plastically changed layer is shown by SEM (Fig. 5). It shows that 3 and 4 passes form thicker layer than 1 and 2 passes. This layer can work like a solid lubricant during friction process and together with hardening of the shaft surface determine the high tribological properties of burnished stainless steel when the passes of burnishing are 3 or 4.

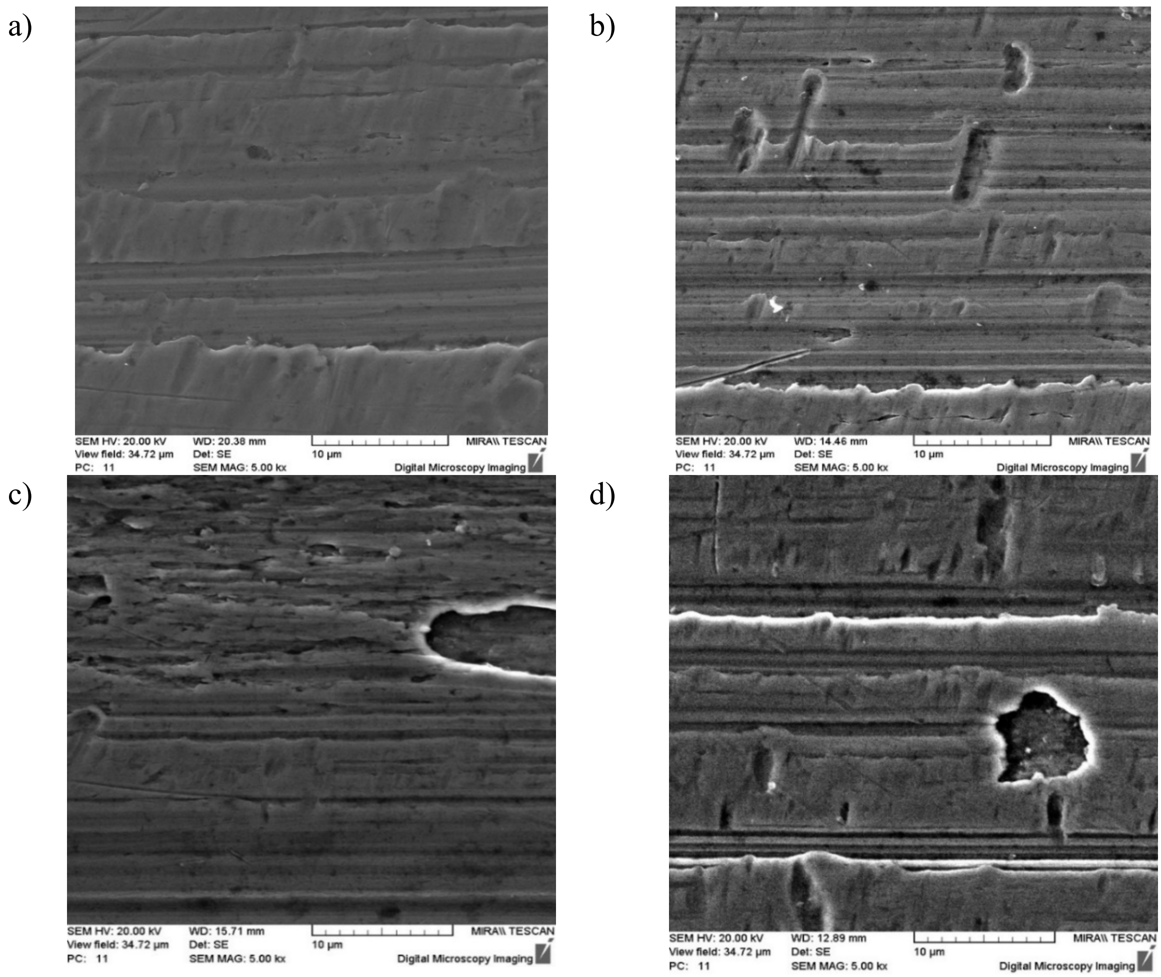

Fig. 5. The morphology of treated surfaces, obtained with SEM: (a) one pass, (b) two passes, (c) three passes, (d) four passes

AFM helps fuller to visualize the microstructure of the changed surface layer (Fig. 6). The images are supplied by profile to appreciate the thickness of the layer on microlevel.

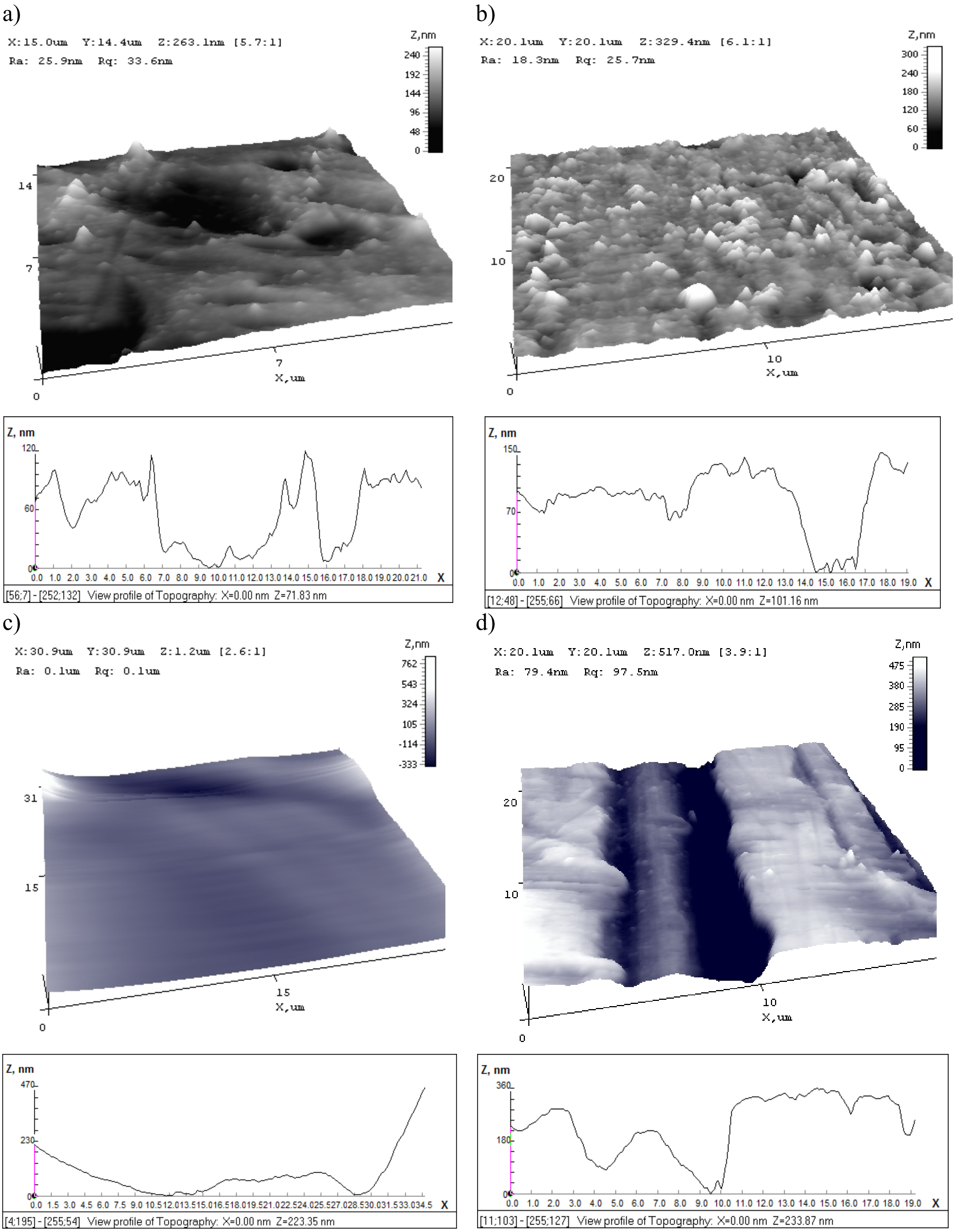

Fig. 6. The morphology of treated surfaces, obtained with AFM on scanning area about 20 x 20 µm: (a) one pass, (b) two passes, (c) three passes, (d) four passes

The surface after one pass of tool even has the areas where the structure is not oriented according to the tool moving (Fig. 6a). The thickness of an average sublayer for one pass is about 100 nm, the roughness on scanning area 20 x 20 μm is 26 nm (Tab. 1). The surface after two passes of tool has the direction of layer orientation but has a lot of microparticles with diameter from 100 nm till 1000 nm (Fig. 6b). The height of these microparticles is similar to an average layer thickness and is about 120 nm. The roughness on scanning area 20 x 20 μm is about 31 nm. The image of surface after three passes shows the changed layer which cover up the surface. This layer is without structure because it is too soft, it is not a solid material. But it is the highest layer with thickness about 470 nm. The roughness of this layer is 66 nm. The stainless steel after 4 passes of burnishing has more expressed microstructure (Fig. 4 d). An average height of sublayer here is about 350 nm. The roughness is about 79 nm. The layer consists of two sublayers: top layer and bottom layer (Fig. 7). All two layers are well-ordered. In regime "Torsion" the bottom layer consists of the rounded particles with diameter 100 – 500 nm, which supposedly are the plastically changed metal particles in more ductile matrix from machine oil after polymerization, but the particles are in a majority. The top layer consists of machine oil after polymerization. This layer has one or two particles. The microstructure consists of thin ductile lines with diameter about 100 nm. The building of both layers from nanoobjects shows that they can easily rebuilt by sliding under the load what provide their effective work as a solid lubricant.

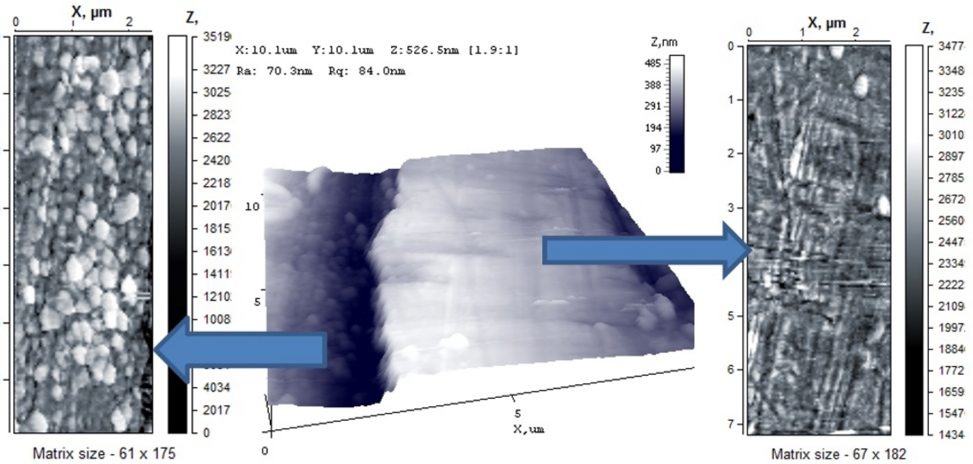

Fig. 7. The features of treated with 4 passes surface morphology, obtained with AFM with images in regime lateral forces ("Torsion") for upper and under sublayers of soft changed layer

The measurement of adhesion forces with AFM shows that the surfaces after 3 and 4 passes tool have the nearest values about 5.2 and 7.3 μN (Tab. 1).

Tab. 1. Properties of the stainless steel shaft surface after burnishing, obtained with AFM

Number of burnishing passes	R_a on area 20 x 20 μm, with AFM, nm	Young modulus of the surface layer on the depth 20 nm, obtained with AFM, GPa	Adhesion forces between surface layer and AFM –tip, μN
1	26	-	9.0
2	31	4.1	8.8
3	66	4.3	5.2
4	79	4.6	7.3

That means that these layers provide the low coefficient of friction in comparison of one and two passes. High adhesion forces between counter parts can influence on coefficient of friction increasing it. The value of Young modulus determined with AFM about 4 GPa are in agreement with the supposition that this layer can work as a solid lubricant because 4 GPa is the level of polymers and when this layer is located on hardened steel surface it can provide more favourable condition for friction.

5. Conclusions

The measurement of microhardness and Young modulus changes from the surface till depth 160 μm were carried out with NI method for stainless shaft surface after burnishing process. The results showed the hardening of the surface till 6-7 GPa from 4.5 GPa. The dependence of Young modulus from the distance, the surface and the number of tool passes during burnishing showed that the best regime is burnishing with 4 passes. In spite of hardening effect of surface layer according to microhardness measurement after one pass of tool, Young modulus measurement shows, that one pass of the tool weakens the properties of under surface layer reducing Young modulus. Burnishing with 4 tool passes provides the increase of Young modulus till 210 GPa on the depth 20 μm under surface.

Surface morphology research were carried out with SEM and AFM showed the presence of third body on the shaft surface – the soft changed layer formed from plastically deformed stainless steel and machine oil under action of load, speed and temperature. This layer has well-ordered microstructure and can rebuilt under acting of the load. The adhesion forces and Young modulus of this changed layer about 4 GPa, determined with AFM, enable to observe it as a solid lubricant. Therefore, the presence of soft layer on the hardened steel surface with increase of Young modulus value till 210 GPa on the depth 20 μm enables to recommend four tool passes by roller burnishing for the aim of forming the detail for tribological application like the pumps shaft.

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