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The Improvement of Machine Elements Working Capacity by Means of Nanotechnology

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Abstract

It is shown that the surface nanocrystalline structure with raised microhardness, low friction ratio is formed in the process of mech-pulsed treatment based on the use of high-speed friction energy. Dependence of the parameters of hardened layer and surface condition on the technological treatment schedules is identified. The high wearing quality of the hardened surface layer and the prospects of its use to improve the working capacity of machine elements are shown.

Key words: *nanocrystalline structure, mech-pulsed treatment, microhardness, wearing quality*

In recent decades, the increase of operational life of the structural steel was reached by the development of alloys with the new chemical and phase composition. At this time, a new way to control the properties of metals by purposeful formation of micro- and nano-crystalline structure (NCS) is found. One of the ways to obtain the NCS is the severe plastic deformation (SPD) working in the same direction as the alloyage and heat treatment [1]. There are methods for producing bulk [2] and surface NCS [3]. The surface is responsible for such operational characteristics of machine elements (ME) as fatigue, wear, contact endurance, corrosion and erosion damage, cavitation and others. The production technology of surface NCS SPD by high-speed friction of mech-pulsed treatment (MPT) is developed in the Karpenko Physico-Mechanical Institute of the NAS of Ukraine. It is kinematically similar to grinding (Fig. 1) and implemented on manufacturing lathes [4] or surface grinding machines through their minor revamping.

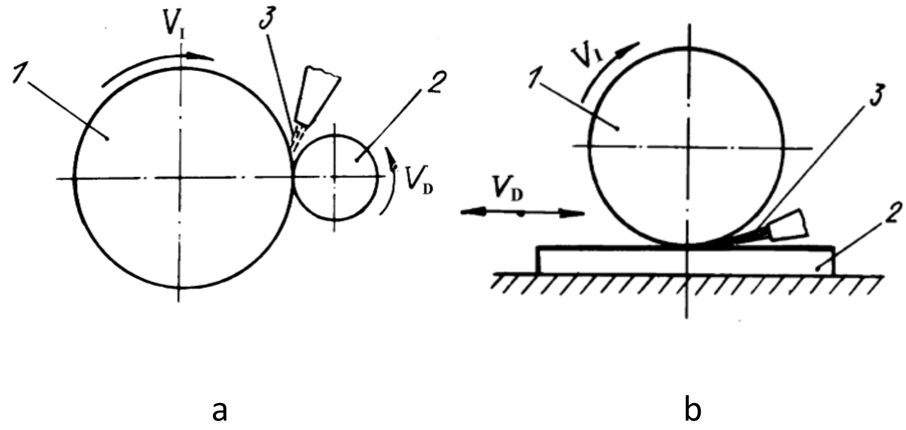


Figure 1 MPT scheme of cylindrical (a) and flat (b) surfaces: 1 - reinforcing tool; 2 - workpiece; 3 - process environment (PE)

The core of technology is the metal surface layers heating by the speed friction up to temperatures above the point Ac_3, the simultaneous thermoplastic deformation and the subsequent blast cooling at the speeds of 10^3–10^4 ºC/s by removing heat from the surface layers to the tool, the element and process environment (PE). The result of MPT is the structural phase changes in surface layers and the formation of gradient finely crystalline structure of nanometer range (15-30 nm) of mainly martensitic type with the value of microhardness 6-12 GPa. The surface layers saturation by alloying elements from the polymer PE occurs in the speed thermoplastic deformation conditions. It is appropriate to use the PE for cementation [5] or nitrogenization during the low carbon steels treatment. It further improves the physical, mechanical and corrosion properties of the surface layers.

The hardening tool is an important factor affecting the temperature-power conditions in the area of frictional contact (FC) during the MPT. The temperature in the FC area depends on the friction ratio of the hardening tool and element [6]. The heat generated in the FC area is absorbed by the hardenable element, tool and PE. Heat flows into the tool and the element depend on the ratio of their speeds [7]. More heat is absorbed by the faster rotating body. Since the tool speed is much more than the element speed, the main amount of heat is absorbed by the tool. To prevent this, the tools are made of materials with the high friction ratio and low heat conduction. Stainless steels and titanium alloys most meet the requirements. The temperature reaches up to 850-1500 K in surface layers under such conditions (Fig. 2). The use of titanium alloy tool provides the maximum temperature in the surface layers of hardenable element. The speed thermoplastic deformation (10^2-10^3 c^{-1}) occurs due to the severe shear deformations in the FC area [8].

It was found [8] that the dispersion of grain structure of the steel sample surface layer from the micro- to submicro- and nanoscale occurs in the SPD process during the MPT. The surface layer structure formation in the SPD process has a multilevel nature and is implemented on the new, high structural dispersion levels with the increase of deformation speed rate. As the surface layers are heated in the FC area to temperatures above the Ac_3 and cooled below the Ac_1 points during the MPT, they pass structural-phase transformations, which in most cases lead to the martensite-austenite structure formation. The grain size, structural-phase composition, and thus the microhardness and depth of the hardened layer varies depending on the tool material (Fig. 3).

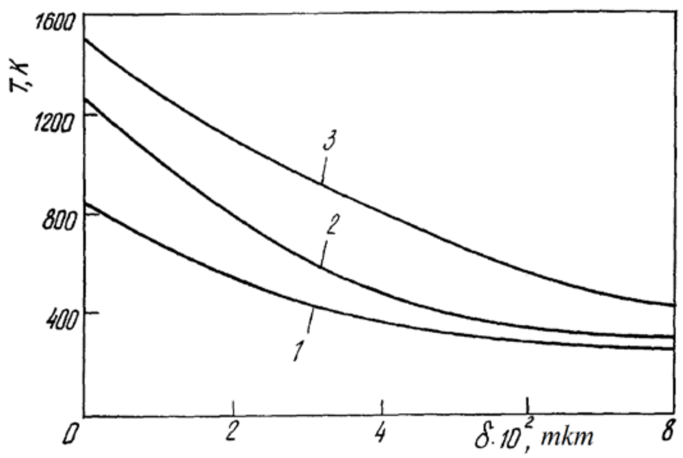


Figure 2 Temperature distribution in the element depth during the steel 45 (pearlitic ferrite) hardening by the tool made of different materials: 1 - steel 42Cr4; 2 - steel 12Cr18Ni9Ti; 3 - alloy WTi6, PE - air

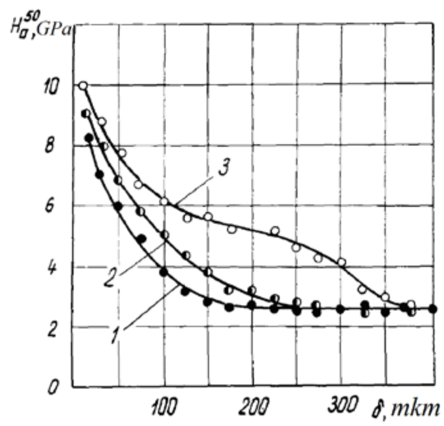
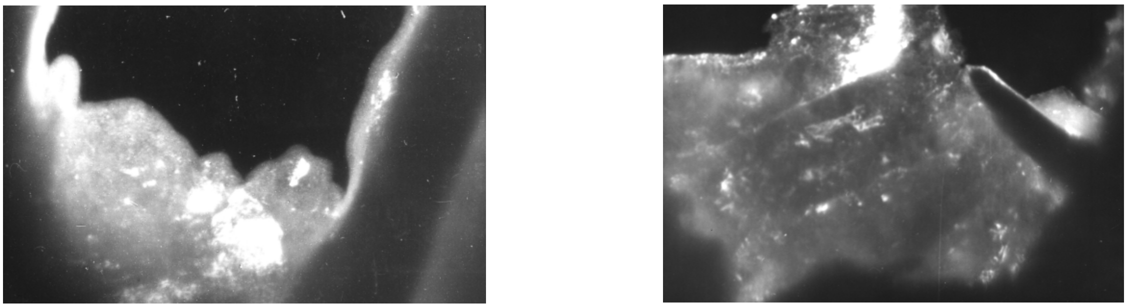


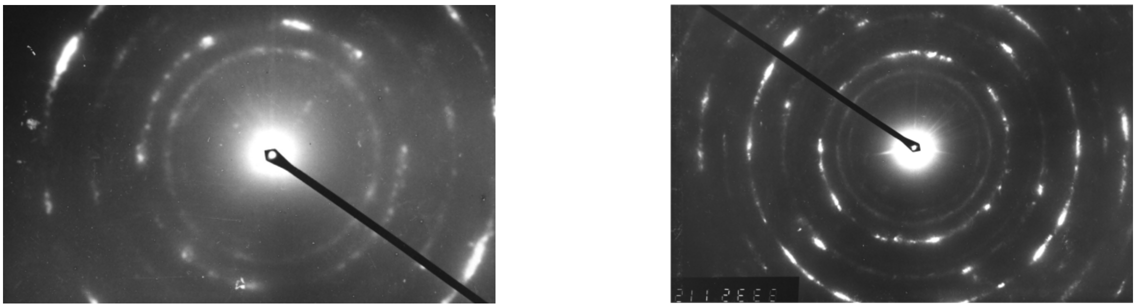
Figure 3 Microhardness distribution on the steel 45 after the MPT by the tool made of different materials: 1 - steel 42Cr4; 2 - steel 12Cr18Ni9Ti; 3 – titanium alloy WTi6

Fig. 4 shows an electron microscope image of the structure of steel 45 at different depths after the MPT, and Fig. 5 - diffractograms taken at the same depths. The structure is highly fragmented and the degree of fragmentation increases as it approaches the surface. It is confirmed by the results of submicroscopical studies of the films on the microstructure lumen of the hardened layer. The main feature of the NCS received by the intense plastic deformation is the presence of non-equilibrium grain boundaries serving as a source of high inherent stresses. Curved contours of the boundaries in grains are the proof of this (Fig. 4). Nonequilibrium grain boundaries have a large number of dislocations, and uncompensated disclinations are concentrated in tripartite conjunctions. The dislocation density reaches $1{,}6\times10^{12}$ sm^{-2}. Dislocations and disclinations form a long-range stress fields, serving the cause of the excess energy of the grain boundaries [2].



a *b*

Figure 4 Electron microscope image of the structure of steel 45 at the depths of 10 (a) and 15 mkm (b) from the surface after the MPT in PE for cementation [5]



a *b*

Figure 5 Diffractograms of the structure of steel C45E taken at the depth of 10 (a) and 15 mkm (b) from the surface after the MPT in PE for cementation

The maximum fragment size is less than 25 nm at a depth of 15 m in the hardened layer, while the matrix grain size is 1-4 mkm. The splitting of individual diffraction reflections into groups is observed on the electron-diffraction patterns of hardened layer. It confirms that the collective forms of dislocation ensemble evolution cause not only translational plastic shears of adjacent parts of the crystal, but also their plastic reversals in the process of thermoplastic deformation. The maximum azimuthal splitting of reflexes in the microdiffraction area (1 mm) is less than 6°. This is a large-angled boundary and, therefore, the fragment is grain. A more fragmented structure is observed at a depth of 10 mkm. Their spatial disorientation increases. The maximum azimuthal splitting of reflexes in the microdiffraction area is already 10°. The degree of crystallite fragmentation increases while approaching the surface.

The important parameters of the hardened surface layer are its depth, microhardness, surface roughness. They depend on the hardening modes, reinforcing tool material, penetration depth (pressure force) of tool, element rate speed, longitudinal feed of tool. The tool crushes microroughnesses and the segregation takes place as a result of heating and high pressure in the FC area. Fig. 6 shows the change dependencies of the hardened layer thickness and segregation value depending on the treatment schedules when using the tool from steel 42Cr4 and its rate speed of 50 m/s. PE is fed into the FC area for cementation [5]. The hardened layer thickness δ increases monotonically (Fig. 6), and the segregation Δd decreases dramatically with the increase of longitudinal feed S in the range of 0.8-2.0 mm/rev. The longitudinal feed is increased by the treatment force, and therefore, the power, which is converted to thermal energy in the FC area. It leads to the hardened layer depth increase. The increase of tool penetration depth t in the range of 0.2-0.4 mm similarly leads to the growth of the strengthening forces components and, respectively, to the hardened layer depth increase (Fig. 6b). When the penetration depth is more than 0.4 mm, the hardened layer thickness is reduced due to the spitting of its surface layer and the metal removal from the contact area. The increase of hardenable element rate speed leads to the reduction in the hardened layer depth δ and segregation Δd (Fig. 6c). It is related to a decrease in the residence time of the hardenable element corresponding zone in the FC area and correspondingly to a decrease in depth of metal warming. It should be noted that the hardened layer depth most of all depends on the carbon content in the steel and can reach 0.8 mm on high carbon steels with the microhardness of 10-12 GPa. The hardening of steels in the improved condition also leads to the hardened surface layer thickness increase.

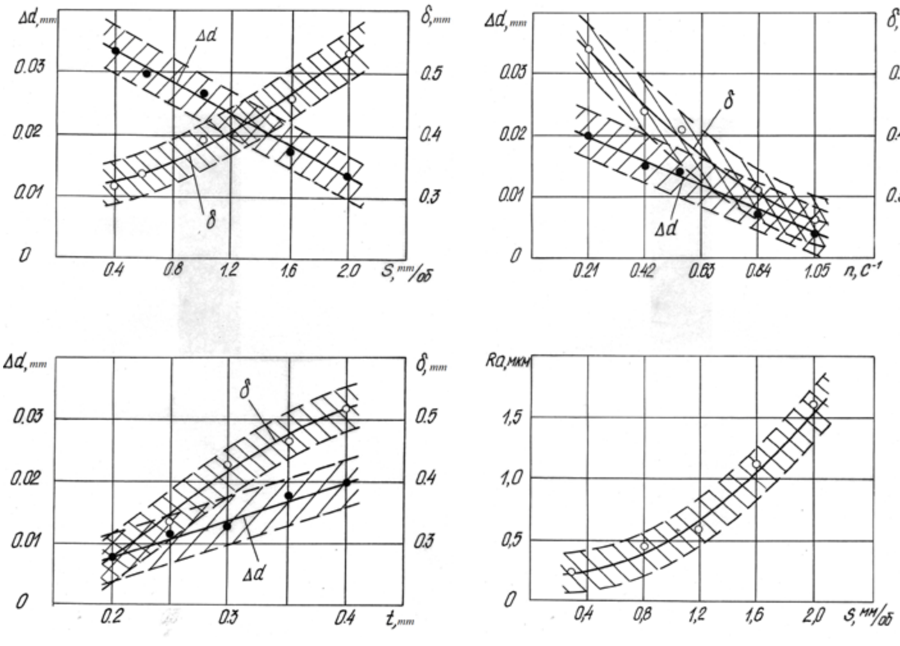
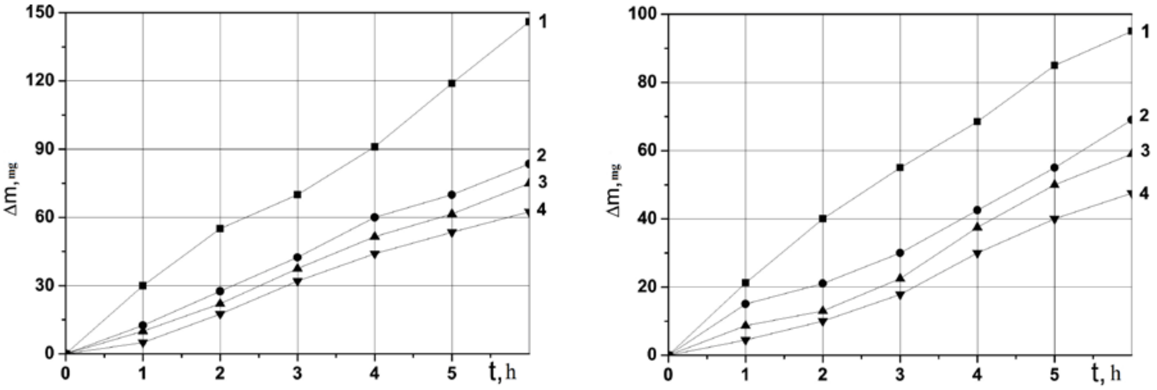


Figure 6 A change of the hardened layer thickness (δ) and the segregation value (Δd) on the 20 mm diameter cylindrical specimens of steel C45E (pearlitic ferrite) depending on the longitudinal feed S when n = 0.83 c^{-1}, t = 0.3 mm (a) the element rate speed n when S = 1.5 mm/rev, t = 0.3 mm (b), the penetration depth t when n = 0.83 c^{-1}, S = 1.5 mm/rev (c) and the roughness on the longitudinal feed S when n = 0.83 c^{-1}, t = 0.3 mm (d)

The reinforcing tool geometry and longitudinal feed mainly affect the hardenable surface roughness. The longitudinal feed increase leads to the deterioration of the surface roughness (Fig. 6d), wherein the hardened layer depth increases (Fig. 6a).

The nanocrystalline structures in general [2] and obtained by this treatment in particular have a reduced (1.5-4 times) friction ratio. It leads to an increase in steel wearing quality for dry friction in the oil and oil-abrasive environments.

Fig. 7 shows the kinetics of the steel C45E wear after the MPT in different PE and using a special reinforcing tool. Tests were carried out under the ring - liver scheme on the friction machine SMC - 2. Different types of MPT were compared with the chromium plate, which is used in some cases to protect the surfaces of machine elements (blinds of hydraulic cylinders) from wear. In all cases (curves 2, 3, 4) the MPT treated samples provide a higher wearing quality of friction couple, compared with a chromium plate. The MPT is most effective using the PE for cementation and hardening by the special tool during the alloyage by copper [9]. Specified dependencies are saved with the specific pressure rise above 2 MPa with increase of the friction couple mass losses. It should be noted that the use of MPT only for the rings also increases the wearing quality of livers, due to the decrease of a couple friction ratio.



a *b*

Figure 7 Kinetics wear of a couple steel C45E - steel 100Cr6 with rubbing in the oil-abrasive environment of ring (a) and liver (b): 1 - coating by Crh.24; 2 - MPT in mineral oil; 3 - MPT in PE for cementation [5]; 4 - MPT with copper rubbing by special tool [9]; (υ = 0.9 m/s, P = 2 MPa; oil TAP - 30 + 0.1% from wt. abrasive)

Conclusions

The MPT technology passed the pilot testing and is implemented in the production for the treatment of protection sleeves, discharge rings and disk pumps, barrel collars of the drilling unit swivel, saddles and plates of drill pumps, pins of conveyors and elevators, blades of shotblasters, hydraulic-cylinder rods, etc. The service life of elements increases 1.5 - 4 times, depending on the operating conditions of elements with the treatment cost increase by 25-30%. MPT is potential for the hardening of metallurgical equipment (hot reducing rollers, mandrels, simple male punches for the inner diameter of pipes forming, drill pipes, etc..)

Thus, the mech-pulsed treatment, based on the high-speed friction principles, forms in the surface layers of steels of NCS with a high microhardness, reduced friction ratio and high wearing quality. The application of technology can increase the interrepair cycle, eliminate the downtime, reduce the deficit of service parts and the energy consumption.

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