Applied Mechanics and Materials Vol. 630 (2014) pp 397-412
Online available since 2014/Sep/19 at www.scientific.net

doi:10.4028/www.scientific.net/AMM.630.397

Upgrading of Pump and Compressor Rotor Shafts Using Combined Technology of Electroerosive Alloying

Viacheslav Tarelnyk[1,a*], Vasyl Martsynkovskyy[2b]

[1]Sumy NAU, Kirova Str. 160, Sumy, 40021, Ukraine

[2]TRIZ Ltd, Mashynobudivnykiv Str.1, Sumy, 40020, Ukraine

[a]tarelnik@i.ua, [b]mbc@triz.sumy.ua

Keywords: combined technology, electroerosive alloying, surface plastic deformation, ball burnishing, diamond smoothing, microhardness, surface layer, combined electroerosive coating, repair.

Abstract. The upgrading technology of rotor shaft necks in the process of their manufacture and repair was developed on the basis of the stressed-deformed state analysis, structure and properties of the surface layer, subjected to electroerosive alloying with the further surface plastic deformation.

Introduction

As a rule, machine parts breakdowns during operation are caused by the processes, carrying in the surface layer, such as stress concentration, microcrack development, alloying elements burnoff, softening, wear, oxidation, residual stress redistribution, etc.

In order to increase such operational characteristics of machine parts as fatigue strength and wear-resistance, the methods of surface plastic deformation (SPD) are widely used.

The essence of the SPD method consists in the following: under pressure of the moving deforming element (for example, roller, ball or smoother), the metal of inequalities projections and a thin surface layer in the place of contact with the deforming element is plastically deformed and moved, being under condition of three-dimensional stress state, flowing in adjacent hollows and squeezing out upwards. As a result, a qualitatively new surface with inequalities of a specific shape is formed, which could not be achieved by means of edge cutting and abrasive machining.

The following is typical for newly formed microrelief of the hardened surface: high ratio of inequalities width to height; high degree of inequalities uniformity either by shape or height; small angles of slope; big spherical radii of projections peaks and hollows bottoms that defines a flat streamlined shape of inequalities. Along with inequalities smoothing, the layer hardness increases with formation of compressive stress in it.

The coatings, which can be formed using various methods, are of great practical importance in engineering. Their main task is to improve the qualitative parameters of surface layer: microhardness and wear-resistance increase, recovery of worn out surface areas, etc.

Approach

One of the advanced technologies of machine parts surface upgrade is the method of electroerosive alloying (EEA). Its advantages are the automation simplicity, “installability” in technological process of machine parts manufacturing and operations overlapping. It is universal and applied for: increase of hardness, resistance to corrosion, wear and heat resistance; decrease of surface adhesion in friction; recovery of machine parts and mechanisms dimensions; micrometallurgic processing for formation of required chemical compounds on the processed surface; creation of transition layers of certain roughness on the working surface, etc. [1]

In spite of the advantages, EEA method has a series of disadvantages as well (increase of surface roughness, formation of tensile residual stress in the surface layer, decrease of fatigue resistance), which often limit the scope of use for a more wide range of machine parts.

Apparently, the use of SPD in combination with EEA of the surface layer is of special interest, as these technologies complement each other [2-4]. However, insufficient quality of data, concerning the analysis of SPD processes of surface layers, prehardened by EEA, retards the development of the considered work-hardening technologies. Consequently, the work of this direction is of great importance nowadays.

The aim of the work is to increase the quality of rotor shaft journals during their manufacturing and repair using computation algorithm of the technological parameters for the action with SPD methods on the surfaces, subjected to EEA.

The analysis of strain-stress state of the surface layer after EEA and further SPD method.

Calculation method of the deformation zone geometrical parameters for surface layers with the complex structure, obtained in the process of EEA, is stated below. This method was developed on the basis of M.S. Drozd's engineering method for calculating the main geometrical parameters of the deformation zone for homogenous bodies, which is based on the concept of plastic hardness (НД).

For ease of comparison with the Brinell hardness method, the following proportion was suggested to be considered the plastic hardness *HD* number:

$$HD = \frac{\mathrm{P} - \mathrm{P_0}}{\pi \mathrm{Dh}}, \tag{1}$$

where P – arbitrary load; P_0- critical load, numerically equal to intercept of linear approximation of function P= f(h) on the axis P; D – diameter of introduced ball; h – depth of residual dimple.

Transition from hardness HB, the parameter, characterizing metallic resistance to contact load, to plastic hardness *HD*, interpreted as module of material hardening, renders possible to consider this value as characteristics of material resistance to contact plastic deformation. It should be noted that in case of SPD of hardened by EEA layers, such characteristic of their physical and mechanical properties is more physically substantiated and convenient, as it defines actually the layer hardenability in the process of SPD method, and therefore the change of operational properties of this layer.

It was previously discovered that formation of structure of the surface EEA layer mostly depends on the hardness of the alloy electrode material and consequence of layers application [5]. It was also stated that in case of EEA with hard wear-resistant materials, a "white" layer appears on the cathode (machine part) surface, which has, as a rule, the hardness notable higher than the hardness of the main metal. There is a transition layer underneath a "white" layer- a sublayer as a zone of thermal influence of impulsing discharges and diffusive interpenetration of the anode and cathode elements. Hardness of this zone changes in depth smoothly in comparison with "white" layer hardness.

In case of EEA with soft antifriction materials, the microhardness of surface layer decreases significantly, changing thereby the mechanism of surface layer hardening.

Combined electroerosion coatings (CEC), depending on the consequence of hard and soft materials application, may have different microhardness either on the surface or in depth. For this reason, considering CEC for their further SPD hardening, the hardening process depending on microhardness may be identical to hardening the layers of hard, wear-resistant materials in the first case and of soft antifriction materials in the second case.

Considering the mentioned above, it should be noted that upgrading EEA layers using SPD method (roughness decrease, microhardness increase, etc.) mostly depends on the structure of the doped layer and on correctly chosen modes of force action on it.

In the process of EEA either with hard wear-resistant materials or soft antifriction materials, excluding carbon alloying (with graphite electrode), workpiece thickness increases by thickness of the formed EEA layer (Δh_c)

In the case of EEA of a shaft, its diameter ($D_В$) will increase by 2 Δh_c.

We shall consider the change of geometrical parameters of the contacting bodies depending on structure microhardness of the formed EEA coatings.

When there is a hard coating (Fig.1, a), a spherical indenter, exposed to load P applied, presses a solid “white” layer into the more soft transient sublayer, hardening the last one. “White” layer serves as intermedium, increasing the radius of the indenter action by the value, equal to thickness of the “white layer” ($\Delta h_{б.с}$), and decreasing the shaft diameter by $2\Delta h_{б.с}$.

When EEA is performed with soft antifriction materials (Fig. 1, b), the value of the spherical indenter radius remains the same and the shaft diameter increases by $2\Delta h_{c.}$ In this case, both soft surface layer and sublayer (transient layer) are subjected to deformation and hardening.

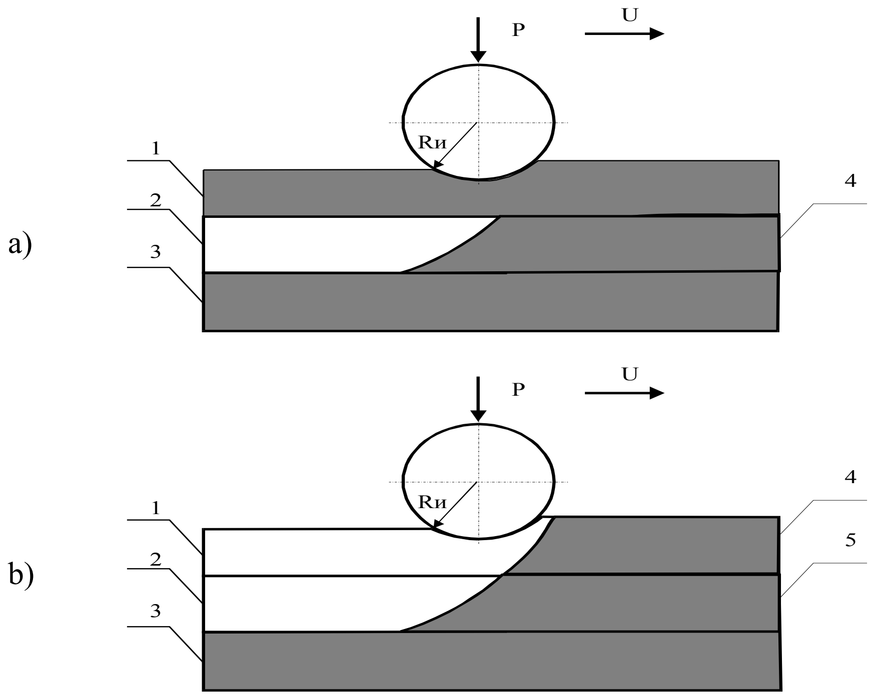


Fig. 1. Scheme of SPD of electroerosive coatings, made of:
a) hard wear-resistant materials: 1- non-deforming “white” layer; 2- hardened transient layer; 3- base metal; 4- non-hardened transient layer;
b) soft antifriction metals: 1- hardened surface layer; 2- hardened transient layer; 3- basic metal; 4- non-hardened surface layer; 5- non-hardened transient layer

Last time, carbon alloying (with graphite electrode) with further SPD processing is increasingly used in repair technology for rotor shaft bearing journals. Carbon alloying is a method of cementation with electroerosive alloying (CEEA) [6, 7]. In comparison with the usual cementation, the method of steel parts cementation with electroerosive alloying has a series of advantages, inherent in electroerosive alloying. First of all, it is a possibility of processing in the local place, absence of distortions and deformation, multiple energy saving, small-sized and transportable equipment, etc.

With EEA cementation, the thickness of hardened layer directly depends on discharge energy and time of alloying. Increasing the discharge energy increases not only the hardened layer depth but also the surface roughness.

SPD processing after CEEA is performed in order to decrease the surface roughness and to increase shaft fatigue resistance. Besides, during the CEEA processing of the previously heat-treated parts, a layer with lowered hardness, so called “hardness collapse” can appear under the layer of high hardness that can be eliminated with further SPD processing.

In [8], for the surface upgrade, it is suggested to apply coating of soft antifriction materials (such as copper, silver) with thickness of 0,02- 0,05 mm per diameter on the cemented layer before SPD processing.

Taking in consideration the above mentioned, one should note that upgrading of the cemented EEA layers with SPD method (roughness decrease, microhardness increase, etc.) mostly depends on the structure of the doped layer and on correctly chosen modes of forced action on it.

Below, geometrical parameters of the contacting bodies are corrected considering the parameters of the cemented layer thickness ($\Delta h_{ц}$) and the layer thickness of soft antifriction metal (Δh_c).

A spherical indenter (Fig.2, a), exposed to load P applied, presses the hard cemented layer into the more soft transient sublayer, hardening the last one. Cemented layer serves as intermedium, increasing the radius of indenter action by the value equal to its thickness ($\Delta h_{ц}$), and decreasing the shaft diameter by $2\Delta h_{ц.}$

The cemented layer thickness can be defined by the traditional method of measuring it on a specimen, made of check test piece.

In the case of EEA with soft antifriction materials, the microhardness of the surface layer decreases, changing thereby the hardening mechanism of the surface layer. After cementation with soft metals, its diameter ($Д_в$) will be increased to $2\Delta h_{c,}$ and the indenter radius will not be changed. Soft surface layer is subjected to deformation and hardening in this case, while the transient cemented layer is not hardened (Fig.2, b).

a)

b)

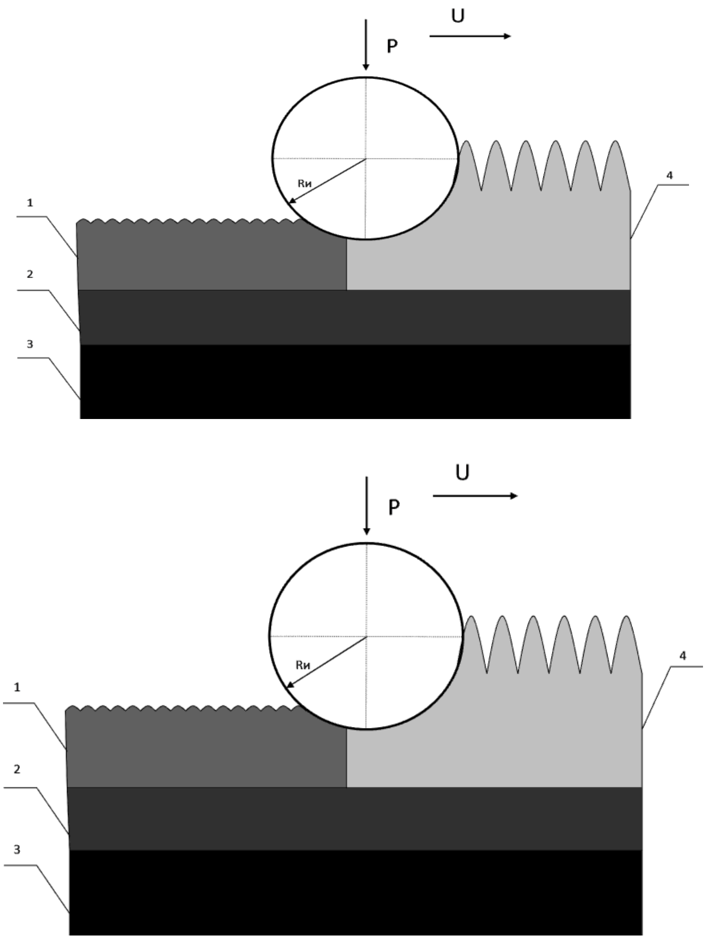


Fig. 2. The scheme of SPD surface layers:
a) after CEEA: 1- hard cemented layer, 2- soft hardened transient sublayer; 3- base metal, 4- unhardened transient layer;
b) soft antifriction metals, applied on the cemented surface layer: 1- hardened soft surface layer, 2- cemented layer, 3- base metal, 4- unhardened soft surface layer

The performed analysis of stressed-deformed state of EEA layers of differential hardness, being subjected to further SPD method, allowed to define the geometrical parameters of deformation zone and depth of cold-worked layer (h_s) and strain intensity (ε_{i0}) for different coatings of hard and soft metals, CEC, and surface layers after CEEA. All the necessary data for calculations are stated in the Table 1, and the results of the research - in the Table 2.

Table 1. Hard, soft and combined EEA coatings and the surface layers after CEEA to be researched

Coating composition	Backing material (DIN)	Layer hardness HD, [MPa]	Layer thickness, micrometer	Equipment
Cr	Steel C 45	3000	30	UILB-8
W	Steel C 45	2800	25	UILB-8
Ni	Steel C 45	2250	40	UILB-8
BK8	Steel C 45	3200	20	UILB-8
Graphite EG-4	Steel C 45	2700	10	UILB-8
Sn	Steel C 45	1000	60	UILB-8
Cu	Steel 41 Cr 4	1700	200	EIL-9
BHC2+Cu+BHC2	Steel 41 Cr 4	2540	400	EIL-9
Cu+BK8	Steel C 45	3000	30	UILB-8
In+BK8	Steel C 45	1800	30	UILB-8
Sn+Cr	Steel C 45	2000	30	UILB-8
BK8+Cu+BK8	Steel C 45	2500	35	UILB-8

Table 2. Results of h_s and ε_0 calculation for samples of steel C 45 and 41 Cr 4 with surface layers of different structure and hardness after SPD with ball burnishing and diamond smoothing

Coating composition	Load, H	A[1]	B[1]	R_{pr}[2]	h[3]	a[4]	b[4]	h_s	ε_{i0}
Ball burnishing									
Without hardening	1470	0.05	0.07	8.4	0.008	0.522	0.443	1.07	0.023
Cr	1470	0.05	0.07	8.4	0.005	0.522	0.443	0.98	0.017
W	1470	0.05	0.07	8.4	0.006	0.522	0.443	1.01	0.019
Ni	588	0.10	0.12	4.6	0.008	0.325	0.296	0.73	0.035
Cr	980	0.05	0.07	8.4	0.005	0.522	0.443	0.96	0.017
Sn	392	0.053	0.072	8.1	0.0071	0.443	0.378	0.88	0.027
Cu	490	0.053	0.072	8.1	0.0042	0.340	0.288	0.75	0.025
BHC2+Cu+BHC2	1470	0.053	0.072	8.1	0.0052	0.522	0.433	1.08	0.017
Cu+BK8	1470	0.053	0.073	8.1	0.0052	0.520	0.441	0.98	0.018
In+BK8	588	0.053	0.073	8.1	0.0048	0.365	0.308	0.80	0.022
BK8+Cu+BK8	1470	0.053	0.073	8.1	0.0058	0.522	0.438	1.09	0.020
Diamond smoothing									
Cr	147	0.170	0.18	2.75	0.0015	0.162	0.153	0.31	0.019
Cr	147	0.250	0.27	1.9	0.0030	0.134	0.118	0.31	0.032
BK8	147	0.170	0.18	2.75	0.0010	0.162	0.153	0.30	0.012
Graphite EG-4	147	0.170	0.18	2.75	0.0020	0.162	0.153	0.33	0.019
Cu+BK8	147	0.166	0.185	2.75	0.0025	0.162	0.153	0.380	0.023
BK8+Cu+BK8	147	0.166	0.185	2.75	0.0025	0.162	0.153	0.380	0.023
Sn+Cr	147	0.166	0.185	2.75	0.0037	0.162	0.153	0.424	0.030

1 – A, B - principal surface curvatures of contacting bodies; 2 – R_{pr} - relative radius of curvature of contacting bodies; 3 – h - residual displacement of contact center; 4 – a, b - semiaxises of residual dimple contour.

Influence of the Main Technological SPD Parameters on Microgeometry, Structure and Properties of EEA Layers

The mentioned above determination of SPD force and deformation parameters of the EEA layers of different hardness allowed to generalize the research results of the surface layer microgeometry, its structure and properties.

SPD modes of samples with diamond smoothing (DS) and ball burnishing (BB) after EEA with chrome, tungsten and nickel are stated in the Table 3.

Table 3. SPD modes of samples after EEA with chrome, tungsten and nickel*

Indenter dimensions (r at DS or Ø at BB, [mm[)	Load on indenter, P, H	Specific deformation force P_{cp}, [MPa[
Diamond smoothing**		
1	150	4500
1	150	4500
1	100	3200
2	150	3000
2	150	3000
2	80	1620
3	150	1920
3	200	2560
3	220	2830
4	150	1330
4	220	1900
4	250	2210
Ball burnishing***		
19	1000	1380
19	1200	1640
19	1500	2060
10	600	940
10	1100	1700
10	1200	1900

* Pass sequence n=1
** Feed S= 0.05 mm/rev
*** Feed S= 0.1 mm/rev

Roughness measurement results are shown in Fig. 3-5 as Ra=f (P_{cp}) curves, where P_{cp} is specific ball burnishing force, determined according to the ratio

$$P_{sp} = \frac{\mathrm{P}}{\pi\ \mathrm{ab}}, \qquad (2)$$

Here P is full ball burnishing force; a, b – semiaxises of the residual dimple contour (see Table 2).

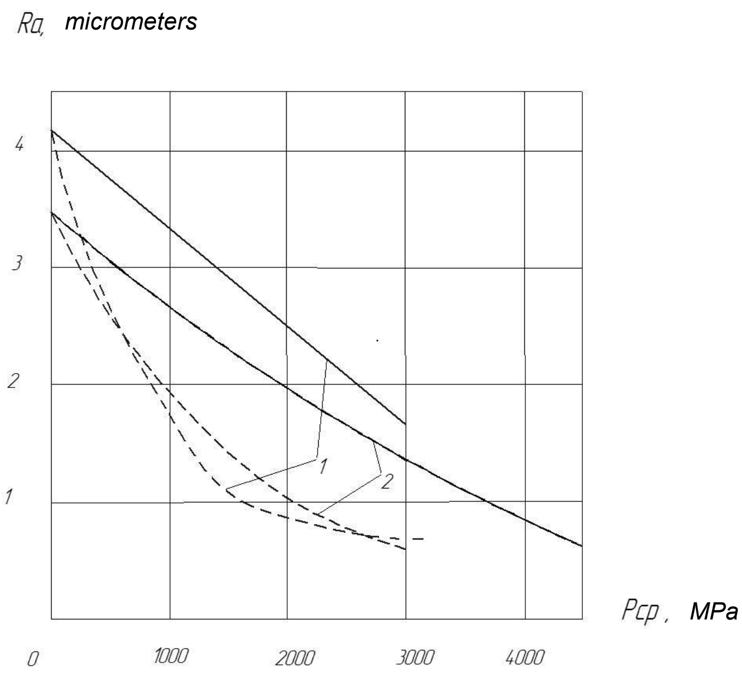


Fig. 3. Characteristic curve of steel C 45 roughness dependence after EEA with tungsten (1) and chrome (2) on specific force of DS at R =1 mm (solid lines) and R=2 mm (dashed)

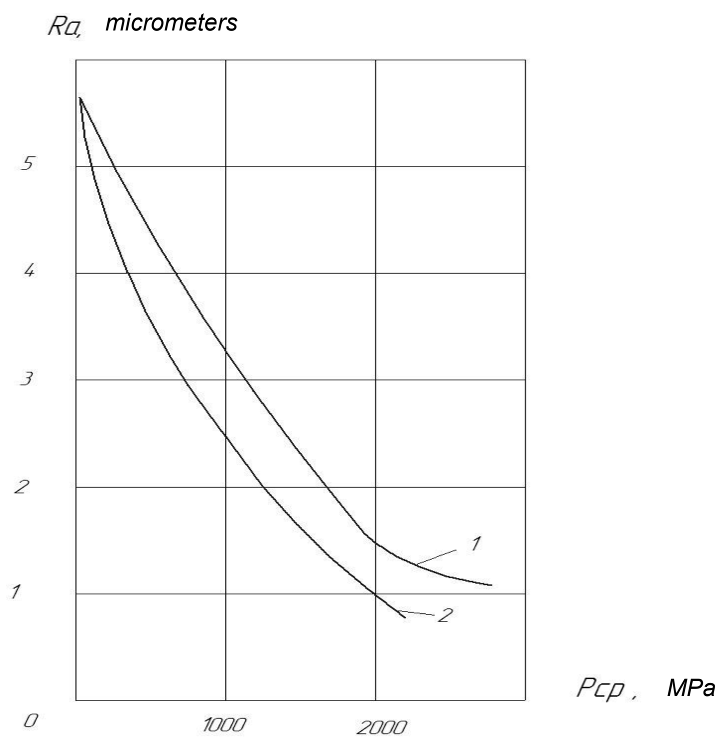


Fig. 4. Characteristic curve of steel C 45 roughness dependence after EEA with nickel on specific force of DS at R= 3 mm (1) and R= 4 mm (2)

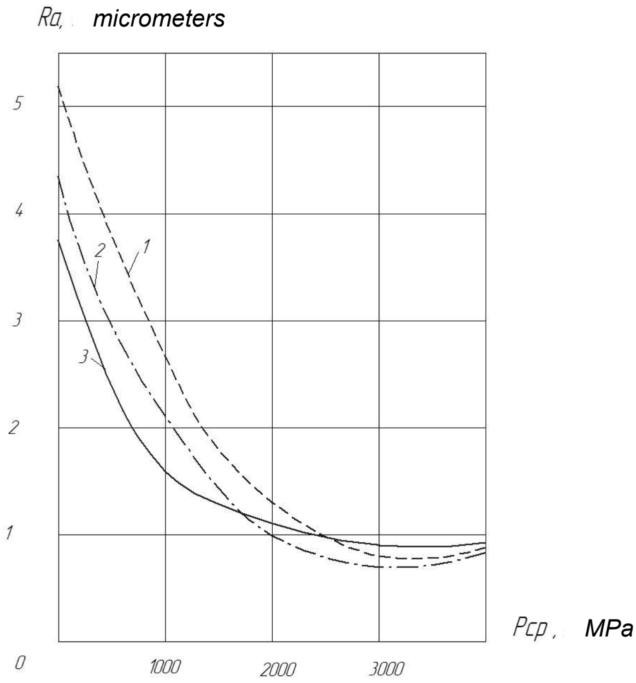


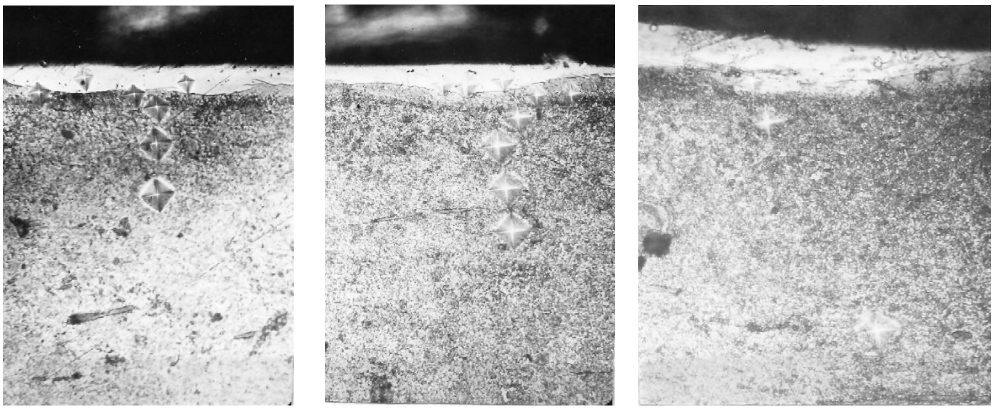
Fig. 5. Characteristic curve of steel C 45 roughness dependence after EEA with nickel (1), tungsten (2) and chrome (3) on specific force of BB

From the data listed above, it follows that SPD efficiency as a method of surface roughness decrease depends on ball burnishing specific force and EEA method. For coatings, made with application of tungsten electrode, the value Ra is determined to a large extent by the radius of diamond indenter, however the effect of indenter radius decreases with increase of coating plasticity (electrodes of chrome and nickel). For the SPD with ball burnishing, it is characteristic that almost all points of the Ra=f (P_{sp}) dependence fall on one curve for all the coatings, irrespective of the EEA type. This fact proves at least that there is a general mechanism of surface forming, combining first of all two processes: deformation of soft coating base and cutting of microroughnesses.

Microstructure analysis of EEA Steel C 45 surface layer with chrome after DS has shown that the more favorable are DS using indenters R=3 mm and R=4 mm with specific force 1920 and 1330 MPa accordingly, (Fig.6, a, b). The burnished surface has minor roughness, with no layer micro failures. Hardness distribution is uniform and smoothly decreases in the level of 7500-8000 MPa with increase of measuring depth. DS using indenter R=4 mm with smoothing specific force of 1330 MPa (Fig.6, b) should be recommended to practical application.

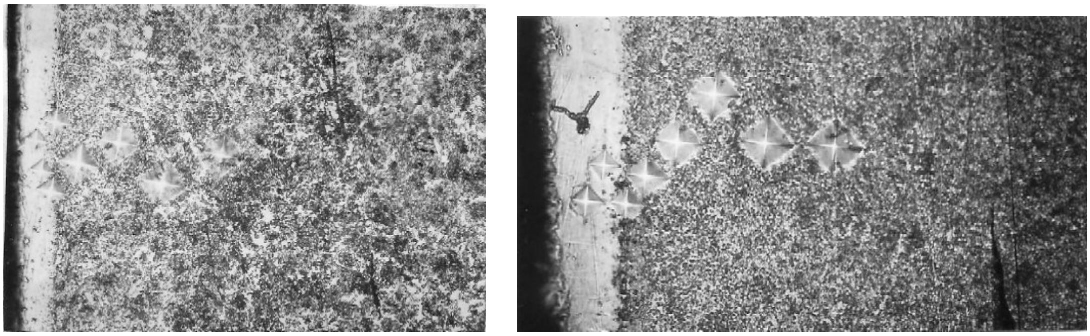
The most favorable situation for chrome coating is ball burnishing with the ball diameter of 10 mm and specific force P_{sp}= 1700 MPa, which provides a layer down practically the whole line of the specimen (Fig.6, c).

The most favorable variant for DS of steel C 45 sample with tungsten coating, which can be recommended for use (Fig. 7, a), is radius of diamond smoothing R=2 mm and P_{sp}= 1620 MPa. In this case, the layer is of good quality with level surface of the specimen line. Hardness of the "white" layer is 7500 MPa, hardness of the transient zone smoothly decreases.



a b c

Fig. 6. Microstructure of surface layers with EEA using chrome after DS: (a – R = 3 mm, P_{sp}= 1920 MPa; b - R= 4 mm, P_{cp}=1330 MPa) and BB: (c - $D_{ш}$= 10 mm, P_{sp}= 1700 MPa) x 400



a b

Fig. 7. Microstructure of surface layer with EEA using tungsten after DS: (a- indenter R=2 mm, P_{sp}= 1620 MPa) and BB: (b - $D_{ш}$ = 19 mm, P_{sp} = 1380 MPa) x 400

When ball of 19 mm diameter and specific force of 1380 MPa are used for BB of steel 45 sample surface layer with EEA using tungsten, the quality of the layer is good: “white” layer with hardness of 8000 MPa, no laps, level surface, no hardness collapse, a gradual hardness decrease from the surface to the base takes place. In the BB sample with ball diameter of 10 mm and specific force P_{sp}= 940 MPa, the layer is of good quality too. When increasing the specific force up to 2060 and 1700 MPa during the ball burnishing with the ball diameter of 19 mm and of 10 mm correspondingly, the damage of the layer is observed. “White” layer is very thin in some places. The most reasonable variant of BB may be the one with the ball diameter of 19 mm and the specific force P_{cp}= 1380 MPa (Fig.7, b).

Availability of a thick applied layer – up to 60 micron is characteristic for steel C 45 EEA with nickel. After DS, the layer becomes thinner and the quality gets worse. High fracture, lapping and tears are observed mostly at all the modes. The layer is practically absent on many samples. From this follows that when a soft layer (H_{μ}= 2000 MPa) is formed by EEA with nickel, DS has a negative effect and its application is undesirable.

Positive effect on the quality of nickel EEA layer has BB. With BB of 19 mm diameter and burnishing specific load P_{sp} = 1380 MPa, the layer of 30 micron thickness and the hardness up to 3000 MPa is formed. The same picture is observed with the BB of 10 mm diameter and burnishing specific load of 940 MPa. The BB of 19 mm diameter and burnishing specific load P_{sp} = 1700 MPa are preferred. In such a case, the layer is uniform along the full length, its hardness is 2800-3000 MPa. The hardness is higher in diffusion zone, it ranges from 4000 to 5000 MPa. Obviously, SPD hardening affects here. The same situation occurs with the BB of 10 mm diameter and burnishing specific load P_{sp} = 2060 MPa (Fig. 8). Hardness increase both in the “white” layer and in the transient zone is also important. With ball burnishing specific force increase, the mechanical hardening of the surface layer takes place, which becomes a significant factor with increase of the layer depth. As a result of cold work, the hardness increases to the level of 6000-6700 MPa, namely to the values of layer hardness, for example, when using EEA with chrome.

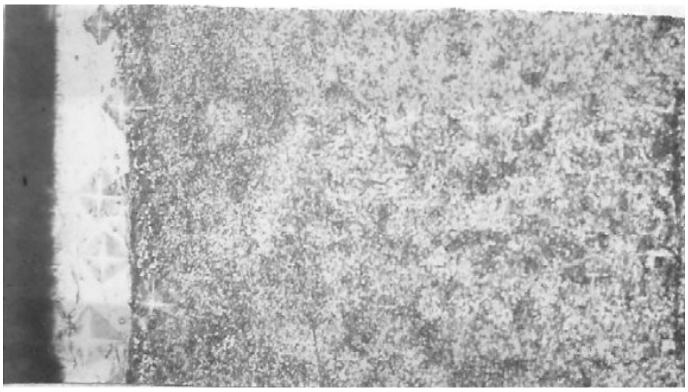
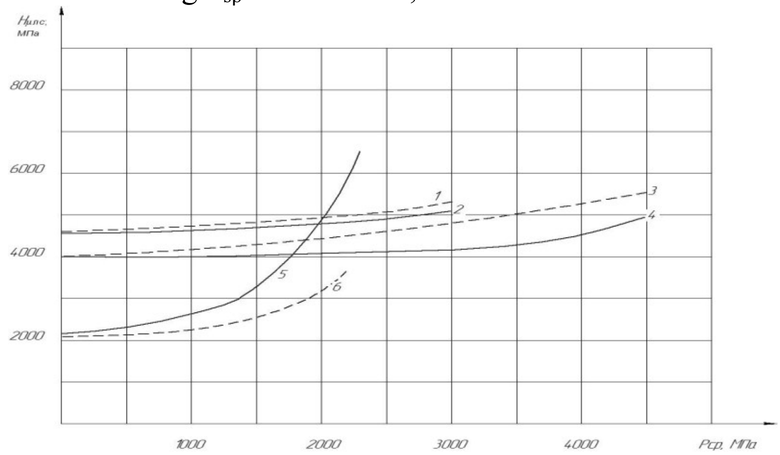


Fig. 8. Microstructure of nickel EEA surface layers after ball burnishing
$D_{ш}$= 10 mm, P_{sp} = 2060MPa x 400

In the case of using preliminary SPD processing, EEA and final SPD, the metallographic analysis shows unacceptability of such a scheme. Practically at all the modes, SPD method causes surface damage, deformation texture, laps.

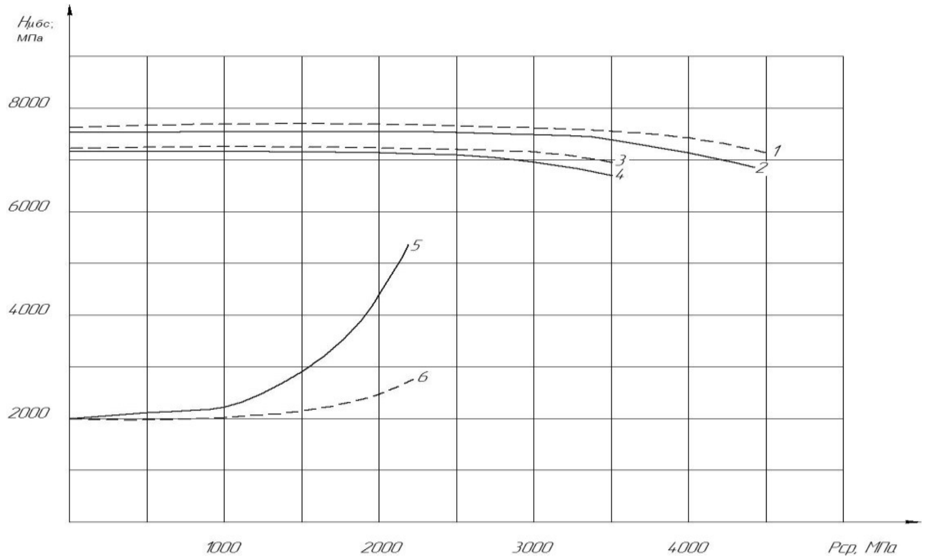
Fig. 9 shows the dependence of “white” layer microhardness of steel C 45 samples with chrome, tungsten and nickel EEA on specific ball burnishing force $H_{\mu.б.с.} = f\,(P_{sp})$ after BB and DS. Both for BB and DS, the microhardness of chrome and tungsten EEA layers doesn’t practically change with increasing the specific force of smoothing (P_{sp}), and only when reaching P_{sp} = 4500 MPa for chrome coating and P_{sp} = 3000 MPa for tungsten coating, it slightly decreases, accordingly from 7500 to 7000 MPa and from 7000 to 6500 MPa. With DS of the nickel coating, the microhardness of the white layer increases slightly, if judging by the microhardness of the surviving areas (from 2000 to 3000 MPa) upon reaching the specific force of smoothing 2060 MPa. BB of the nickel coating shows another picture. Here, with specific force increasing, the microhardness of the white layer increases, and when reaching P_{sp} = 2060 MPa, it amounts to 5400 MPa.



1-Tungsten EEA, DS
2-Tungsten EEA, BB
3-Chrome EEA, DS
4-Chrome EEA, BB
5- nickel EEA, BB
6- nickel EEA, DS

Fig. 9. The influence of DS and BB specific force on the white layer microhardness of steel C 45 samples processed EEA with: 1- chrome, DS; 2- chrome; BB; 3- tungsten, DS; 4- tungsten, BB; 5- nickel, BB; 6- nickel, DS

The dependence of sublayer microhardness of steel C 45 samples with chrome, tungsten and nickel EEA on specific ball burnishing force $H_{\mu.п.с.} = f(P_{sp})$ after BB and DS is shown in the Fig.10. As shown below, microhardness of sublayer with chrome, tungsten and nickel EEA increases with increasing the specific force of smoothing. It is characteristic that with increasing the material plasticity its hardening ability increases. After DS, sublayer microhardness has increased from 4500 to 5000 MPa of the tungsten coating, from 4000 to 5000 MPa of the chrome one and from 2000 to 3700 MPa of the nickel one. After BB, microhardness has increased from 4500 to 5000 MPa of the tungsten coating, from 4000 to 4500 MPa of the chrome one and from 2000 to 6700 MPa of the nickel one.



1-Chrome EEA, DS
2-Chrome EEA, BB
3-Tungsten EEA, DS
4-Tungsten EEA, BB
5- Nickel EEA, BB
6- Nickel EEA, DS

Fig. 10. Influence of DS and BB specific force on the sublayer microhardness of steel C 45 samples processed EEA with: 1- tungsten, DS; 2- tungsten, BB; 3- chrome, DS; 4- chrome, BB; 5- nickel, BB; 6-nickel, DS

In case of steel samples BB, alloyed with soft antifriction metals, with increase of deformation specific force (P_{sp}) the roughness of the surface layer decreases. Burnishing force depends on the microhardness of the coating and the value of original roughness. So, to decrease the surface roughness of tin alloyed steel 45 with the microhardness H_{μ}= 800 MPa from Ra= 4.5 micron to Ra= 0.5 micron, the specific force of deformation approximately of 750 MPa is necessary, while to get the same roughness of the copper alloyed surface with the original microhardness and roughness of 1300 MPa and 12 micron correspondingly, deformation specific force of 1250 MPa is necessary. Further increase of the deformation specific force causes roughness increase, various surface defects. Obviously, the least are original microhardness and roughness of the surface layer, the less is the specific force of the deformation, needed for its smoothing.

Microhardness research of soft antifriction metal coatings shows that the increase of deformation specific force with BB, together with roughness decrease, causes increase of microhardness either in the layer or in the transient sublayer.

In the case of BB force impact on CEC, formed at the manual vibrator unit «UILB-8» and having low original roughness (Ra= 0.48…0.52 micron), almost all points of the dependence Ra= f (P_{sp}) are on one line and the roughness decreases to Ra= 0.1 micron.

The situation is not the same in the case of the force impact of BB on CEC, formed at the mechanized unit «EIL-9» and having the original roughness Ra ≥ 12 micron. In such case, CEC may reach 1 mm and more of thickness, that along with the high roughness and microhardness require much more specific smoothing forces.

Consequently, in order to decrease the roughness of CEC, consisting of high-resistance stainless steel BHC2 and copper, from Ra=12 mm to Ra=1 mm, specific force required to be put is approximately of 3000 MPa.

Metallographic researches of CEC, formed at the manual vibrator unit «UILB-8», show that for getting qualitative surface layers, one should use specific smoothing force of 1000 - 1300 MPa.

If the microhardness of the surface layer is high, for example, the CEC of Cu+BK8 ($H_{\mu} \geq 10000$ MPa) or BK8 + Cu +BK8 ($H_{\mu} = 8000$ MPa), the layer itself is not hardened, but is pressed into the more soft sublayer, hardening the last one. Otherwise, if the microhardness of the surface layer is low, for example, CEC of In + BK8 ($H_{\mu} = 1970$ MPa), the layer itself is subjected to hardening.

The microhardness in the transient layer (sublayer) for all types of CEC increases, but to various extents. Here is the following regularity - the least the original microhardness of CEC sublayer, the more is the reserve of its increase. So, the microhardness of CEC: In + BK8, Cu + BK8, BK8 + Cu +BK8 correspondingly increases from 3500 to 4500 MPa; from 2500 to 4000 MPa; from 2800 to 4000 MPa with increase of BB specific force to 2000 MPa and for CEC of BHC2 + Cu + BHC2 from 2540 to 5000 MPa with $P_{sp} = 4000$ MPa.

The result of metallographic researches of steel 45 samples with coatings of soft antifriction metals (stannum, copper, etc.), subjected to further diamond smoothing SPD has shown that DS is not recommended for soft coatings, as the layer disintegration occurs almost at all the smoothing modes: laps and pits formation, coating material pilling-up on the indenter, layer cutting, etc.

In order to upgrade CEC of high microhardness and low original roughness, applying the DS is possible. The research of the DS specific force effect on the layer and sublayer microhardness of the CEC of Cu +BK8 and BK8 + Cu +BK8 has detected that with smoothing specific force increase, the layer microhardness doesn't change up to $P_{sp} = 1000$ MPa, and then decreases a bit, that indicates the beginning of the formed coating damage, confirmed with the microstructure photographs. The microhardness in the sublayer increases from 2500 to 4500 MPa for the coating Cu + BK8, and from 2800 to 5000 MPa for BK8 + Cu +BK8.

The most rational specific force of the DS, as well as for the hard, wear-resistant coatings, is 1000 MPa.

When upgrading the surface layer subjected to CEEA, SPD method with nonabrasive ultrasonic metal finishing (NUMF) is widely used last time. The application of this method is mostly effective when the layer roughness after CEEA doesn't exceed Ra = 2.0 micron and it can be decreased to 0,6 – 0,8 micron using the method NUMF. If the surface roughness is higher, the coatings of 0,02-0,05 mm thickness per diameter can be applied on the cemented layer using EEA method of soft antifriction (copper, silver, etc.) or more plastic materials (nickel, steel X6 Cr Ni Ti 18 10).

The performed researches recommend the most rational specific forces of the deformation for upgrading the qualitative parameters of the EEA surface layer (Table 4).

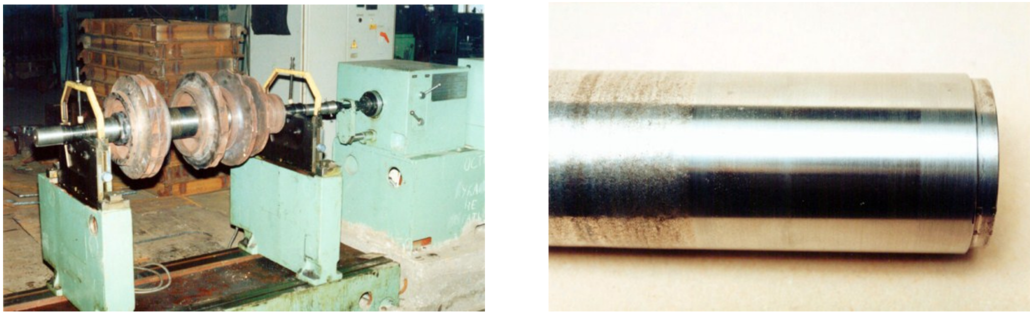
Table 4. The recommended specific forces of deformation for the EEA layers of the various hardness and the results of their impact on microgeometry and nicrohardness of the coatings formed

Coating	EEA Unit	P_{cp}, [MPa]	Ra after SPD, micro meter	Microhardness before SPD, H_{μ}, [MPa]		Microhardness after SPD, H_{μ}, [MPa]	
				layer	sublayer	layer	sublayer
Coatings of hard wear -resistant metals							
Cr	«UILB-8»	BB 1700	0.5	8000	4000	8000	4500
	«UILB-8»	DS 1330	0.4	8000	4000	8000	4500
W	«UILB-8»	BB 1380	0.6	7800	4300	7800	5000
	«UILB-8»	DS 1620	0.6	7800	4300	7800	5000
Ni	«UILB-8»	BB 1700	0.5	2000	2000	3000	5500
	«UILB-8»	DS*					
Coatings of soft antifriction metals							
Sn	«UILB-8»	BB 750	0.5	800	1500	1500	2300
Sn		DS*					
Cu	«UILB-8»	BB 1000	0.1	1600	2000	3000	2500
Cu	«UILB-8»	DS*					
Cu	«EIL-9»	BB 1250	0.5	1300	2100	2500	3000
Cu		DS*					
Combined electroerosive coatings							
In + BK8	«UILB-8»	BB 1000	0.1	1970	3500	5000	5000
In + BK8	«UILB-8»	DS*					
Cu + BK8	«UILB-8»	BB 1300	0.1	10490	2500	10490	3300
Cu + BK8	«UILB-8»	DS 1000	0.1	10490	2500	10490	3200
BK8 + Cu + BK8	«UILB-8»	BB 1300	0.1	8100	2800	8100	3500
BK8 + Cu + BK8	«UILB-8»	DS 1000	0.1	8100	2800	8100	3500
BHC2 + Cu + BHC2	«EIL-9»	BB 2500	1.0	3500	2500	4000	3000
BHC2 + Cu + BHC2	«EIL-9»	DS*					

DS- diamond smoothing
BB-ball burnishing
* - DS is not recommended

Practical application of the integrated EEA + SPD technology for the rotor shaft journals

The repair of the rotor bearing journals of a compressor was performed at All-Union Research Studies Institute Compressormash in Sumy. Fig.11, a shows compressor rotor with the restored shaft journal ∅ 50 mm and Fig. 11, *b* – the journal itself, restored for 0.5 mm per diameter. In this case, steel BHC-2 and copper were applied alternatively as electrode material, and SPD was performed with BB ∅ 19 mm and smoothing specific force of 2500 MPa.



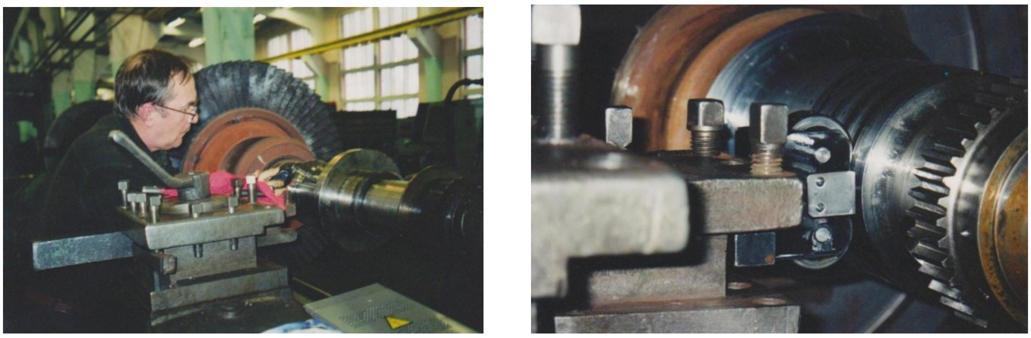
a b

Fig. 11. Compressor rotor (a) with journal ∅ 50, restored for journal bearing (b)

Specialists of TRIZ LTD (LLC) performed the repair of the rotor bearing journals on the turbocompressor GTT – 3 using EEA with further SPD method in Novomoskovsk, EuroChem MCC, OJSC.

Visual inspection of the bearing journals showed that due to the abrasive wear-out, a series of closed cylinder grooves of the various depth and width appeared on the friction surfaces.

The rotor was mounted on a screw lathe with a longish stand, where the areas of journal's tear were polished with abrasive cloth and afterwards were measured. As a result, the diameter of the bearing-thrust journal in various areas reached 149.65 – 149.66 mm, and 149.68 – 149.69 mm of the bearing journal. Figures 12, *a* and 12, *b* show EEA and SPD method of the rotor bearing journals with the ball burnishing.



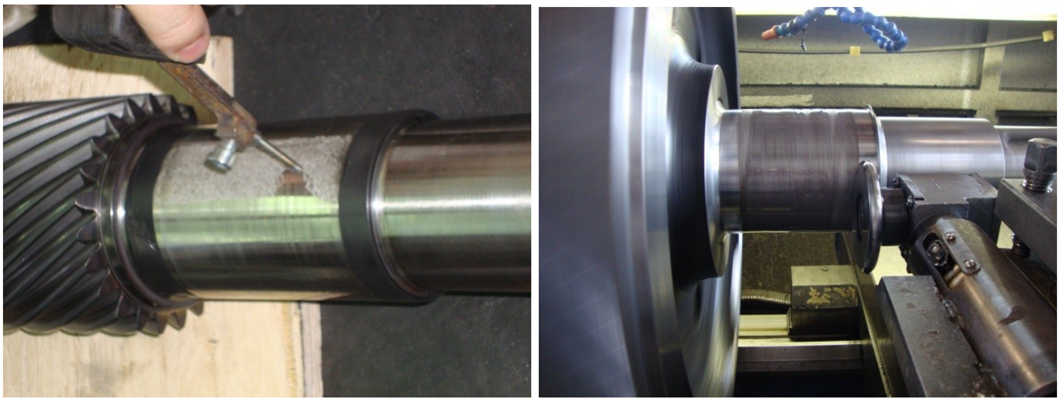
a b

Fig. 12. Repair of GTT – 3 turbocompressor rotor using EEA method (a) with further SPD (b)

Measurement of rotor journals after execution of work showed that their size increased 0.02 mm.

While hardening the teeth of the gear shaft and the gear wheel of the multiplier (Fig. 13) at TRIZ Ltd (LLC), in Sumy, the particulate solids of the abrasive material, used in the course of works, got on the journals of the gear set and caused their damage in the form of scratches up to 0.04 micron of depth.

In the course of repair, the scratches were polished with abrasive cloth and the EEA of the journals was performed with the further application of SPD method. Furthermore, on the gear shaft necks with the diameter from 79.87 to 79.88 mm and the hardness after cementation of 50 HRC, the coating was applied using EEA method with X6 Cr Ni Ti 18 10 steel electrode (Fig. 13, a) and ball burnishing was performed.



a b

Fig. 13. EEA of the bearing journals of the gear shaft (a) and SPD of the bearing journal of the gear wheel (b)

On the gear wheel journal with the diameter from 129.78 to 129.8 mm and the hardness of 180-190 HB, the coating was applied using EEA method with T15K6 hard metal electrode and ball burnishing was performed.

It should be remarked that after application of the EEA and SPD method, the hardness of the gear shaft bearing journals wasn't changed and reached 50 HRC, and the hardness of the gear wheel journals increased to 230 HB.

The multiplier was mounted between electromotor and low-pressure case of the natural gas compressor 22CKO-42/8-38M1 of Methanol work shop at NAK Azot, OJSC.

Consequently according to the results of experimental researches of the main technological parameters of SPD method influence on microgeometry, structure and properties of EEA layers, the following conclusion should be made:

1. SPD effectiveness as a method of surface roughness level decrease depends on specific force of burnishing and EEA technology.
2. The dependencies have been found of surface layers hardness on deformation specific force, which was calculated according to geometric parameters of deformation zone, determined on the basis of stressed-deformed state analysis in the process of SPD method.
3. In accordance with the dependence $H_{\mu} = f(P_{sp})$, it has been discovered that the rational specific force of SPD method comprise 1000 MPa for diamond smoothing and 1500 MPa for ball burnishing.
4. It has been found out that the mostly effective SPD method in the context of the deformation hardening is under condition of initial hardness decrease of the thermal influence zone or presence of a soft sublayer after EEA.
5. All electroerosive coatings are suggested to be divided into three groups to generalize and simplify selection of the most rational deformation force, depending on the microhardness of the coating hardened area: soft (< 2000 MPa), moderate (2000 - 3000 MPa) and hard (> 3000 MPa).

Specific deformation forces are recommended P_{sp} = 750 - 1250 MPa for soft coatings, 1300 - 1500 MPa for moderate ones and 2500 - 3000 MPa for hard ones.

Soft coatings are recommended to be hardened with BB method. The coatings of moderate hardness and the hard ones can be hardened with BB and DS, considering the fact that the roughness (Ra) of the original surface shouldn't exceed 12 micron for BB and 5 micron for DS.

References

[1] Gitlevich A.E., Mikhailov V.V., Parkanskii N.Ya., Revutskii V.M., Electrospark doping of the metal surfaces, Shtintsa, Kishinev, 1985.

[2] Edygarov V.R., Kalunin I.Yu., Degtiar V.V., Classification of the combined processing methods on the basis of electromechanical hardening, Modern high technologies, 3 (2012) 32-35.

[3] Khvorostukhin L.A., Metal coatings processing with smoothing method, Moscow, 1980.

[4] Romanenko D.N., Quality estimation of electrospark surface after ceramic smoothing, Innovation technologies and equipment of machine-building complex: interacademic collection of scientific papers, Voronezh, Volume 10, 62-65.

[5] Tarelnyk V.B., Quality control of the surface layers of machine parts with combined electroerosive alloying, MakDen publishing company, Sumy, 2002.

[6] Martsynkovskyy V.S., Tarelnyk V.B., Belous A.V., Method of steel machine parts cementation with electroerosive alloying, Patent 2337796, The Russian Federation. MPK V 23H 9/00 / Pending 05.10.2006, Edited, 10.04, Bul. N 31, 2008.

[7] Martsynkovskyy V.S., Tarelnyk V.B., Bratushchak M.P., Method of steel machine parts cementation with electroerosive alloying, Patent 66993, MPK (2011); B23H 9/00 / Edited, 25.01.2012, Bul. № 2, Ukraine.

[8] Tarelnyk V.B., Martsynkovskyy V.S., Antoshevskii B., Modern mold forming methods of machine parts friction surfaces, MakDen publishing company, Sumy, 2012.

Problems of Mechanics in Pump and Compressor Engineering
10.4028/www.scientific.net/AMM.630

Upgrading of Pump and Compressor Rotor Shafts Using Combined Technology of Electroerosive Alloying
10.4028/www.scientific.net/AMM.630.397