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Definition of criteria for estimating alternative technologies of increasing quality of rotor shaft neck by electroerosive alloying and surface plastic deformation methods

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Abstract. There are represented the results of influence of the surface plastic deformation (SPD) methods, namely, diamond smoothing (DS) and ball-rolling surface roughness generation (BSRG) ones on the qualitative parameters (residual stresses, fatigue strength and wear resistance values) of the steel substrate surface layers formed by the electroerosive alloying (EEA) method. There are proposed the most rational methods of deformation and also the composition for electroerosive coatings providing the presence of the favorable residual compressive stresses in the surface layer, increasing fatigue strength and wear resistance values. There are stated the criteria for estimating the alternative variants of the combined technologies and choosing the most rational ones thereof.

1. The problem statement

In the practice of mechanical engineering, Coatings, which can be formed in various ways, are of no small importance. Their main purpose is to improve the qualitative parameters of the surface layers of machine parts, namely, increasing microhardness, wear resistance, and also provide an opportunity for restoring a part surface area having been worn out, etc.

One of the promising technologies for improving a part surface quality is a method of electroerosive alloying (EEA). It is a universal method aimed at the followings:

- Increasing hardness, corrosion resistance, wears and heat resistance of a part surface;
- Decreasing the tendency of a part surface to frictional seizure;
- Restoring the dimensions of machine parts and mechanisms;
- Carrying out micrometallurgical processes on a part surface being treated to form necessary chemical compounds thereon;
- Creating a transition layer of certain roughness on a part working surface, etc. [1].

Despite the undeniable advantages, the EEA method has a number of drawbacks such as an increase in the surface roughness, an appearance of tensile residual stresses in a part surface layer, and a decrease in a part fatigue strength, which are often the limits for applying the above said method to a wider range of machine parts.

To increase the performance characteristics of the parts such as durability, wear resistance, the methods of surface plastic deformation (SPD) have been being increasingly used. Obviously, the use of the SPD methods combined with the EEA methods for processing a part surface layer is of particular interest since the above mentioned technologies complement each other [2-4].

In [5], there are represented the results of the investigations of the SPD methods influences on the values of roughness and microhardness for the coatings formed by an EEA method using the electrodes made of soft and hard metals and also their combinations, namely, combined electroerosive coatings (CEC).

In this paper, there are represented the results of the SPD influence on the electroerosive coating qualitative parameters such as residual stress, fatigue strength and wear resistance values, as well as the development of a methodology for determining the most rational alternative technologies to improve the quality of rotor shaft necks. The work carried out in this direction is of current interest.

The aim of the work is to improve the quality of the shaft surfaces of the rotors for dynamic equipment by determining the most rational deformation methods and the proper compositions for the EEA coatings in the course of manufacturing and repairing thereof, as well as setting up the criteria for estimating alternative variants of combined technologies and selecting the most rational one to achieve the above said aim.

2. Research Methodology

To study the SPD influence on the residual stresses of the surface layers having the coatings formed by the EEL method, there were made samples of steel 45 (∅ = 50 mm, L = 200-250 mm). The entire surface of the samples was processed with the use of the EEA method performed by applying hard wear resistant chromium metal, soft antifriction copper metal, and also the combination of the metals to provide the CEC of copper + chromium. Then each sample was subjected to the SPD process carried out using the methods realized by diamond smoothing (DS) and ball-rolling surface roughness generation (BSRG). Each operating condition was matched by a track on a sample of 10 to 15 mm wide.

The DS process was performed on a lathe with the help of a spring-hydraulic device equipped with ASPK-3 smoothers having the vertices radii of R = 3…4 mm depending on the value of hardness of the coating at speed V = 40 ... 80 m / min, smoothing force P = 60 ... 350 N and feed rate S = 0.02 ... 0.07 mm / rev. The BSRG process was carried out on a lathe with a spring-rod device equipped with the ball heads of ∅ 10 and ∅ 19 mm. The maximum breaking-in force for the ∅ 10 ball is 1200 N, and for the ∅ 19 mm ball is 3000 N. Feed rate S = 0,05 ... 0,21 mm / rev, speed V = 30 m / min. Lubrication was made with industrial oil.

The investigations of the axial residual stresses, which are the most dangerous stresses for shafts, were performed using the prismatic specimens made of steel 45 and having dimensions of 70 x 5 x 2 mm according to the method of I.A. Birger providing a stratified process of electropolishing stressed layers on the unit of the Pion type.

Based on the results of the investigation, there were constructed the graphs of the residual stresses depth distributions for the samples of various series.

At least three samples were examined within each series. In the course of the residual stress investigation, the state of a surface layer was determined for the following series:

EEA Cu; EEA Cu + EEA Cr; EEA Cu + SPD; EEA Cu + EEA Cr + SPD.

It should be noted that EEA processes performed by copper and chromium were produced on a unit equipped with a hand-held vibrator UILV-8, respectively, at the discharge energy of W_u = 0.01J and W_u = 0.2 J.

The copper coating SPD process was produced by the ball-rolling surface roughness generation process with the use of the ball head of ∅ 19 mm at the force of 500 N, and the SPD process of the CEC obtained by the Cu + Cr EEA method was produced by the BSRG process with the use of the ball head of ∅ 19 mm at the force of 1500 N.

The fatigue tests were carried out based on $1x10^6$ cycles on the UP-50 machine. To determine the fatigue strength, there were manufactured the 450 mm long samples made of steel 45 each and having the working diameters of 50 mm.

The fatigue strength was determined with an accuracy of 10 MPa for the same series of the samples as those having been used to determine the residual stresses.

The wear resistance values of the coatings were determined on the friction machine of SMC-2 type according to a disk-pad scheme. The disk was a round sample having the outer diameter ∅ 50 mm and the thickness of 10 mm made of 40HN steel. Babbitt B-83 was used as a material for a counterbody (the pad). With applying the EEA method, the surface of the disk was coated with chromium, tungsten, and hard alloy VK8 and CEC: EEA Cu + EEA W + BSRG; EEA Cu + EEA VK8 + BSRG, and EEA VK8 + BSRG + EEA Cu + EEA VK8 + BSRG. The lubrication of the friction surfaces was carried out under conditions when the lower part of the round sample was arranged in a tank filled with turbine oil T-22. The sliding speed was 0.78 m / s, the specific pressure was 5.0 MPa, the load on the pad was 1000 N, the test duration was 8 h, which corresponded to the friction path of 22.5 km. Before the tests, the counterbody made of Babbitt was bored on a lathe in a special device until the friction surface had coincided with a diameter tolerance corresponding to a sliding fit. The surface roughness of the counterbody was Ra = 1.6 μm. Then the samples were set on the friction machine and had been running-in for an hour under the specific load of 2.0 MPa. The process of running-in was deemed to be over when the portion of the treated surface was at least 95% of the nominal one.

To measure a linear wear, onto the working surface of the tested round sample on the Vickers hardness tester, there were made four grooves on diametrically opposite sides. To determine the integral wear of the entire surface, before the test, the sample was weighed with an accuracy of 0.0001 g on the analytical scales of the VLA-200 type.

The linear wear was determined with the use of the method of artificial basis by the depth difference of the prints measured before and after the experiment, and the integral (weight) wear was determined as the weight difference of the sample before and after testing.

In addition, the friction torque was measured in the course of the operation. At the same time, there was monitored the sliding speed and the load in the friction zone.

3. Results and discussion

The most dangerous indices for the fatigue strength of the alloyed shafts are the axial residual tensile stresses, which increase the amplitude of the actual stresses and contribute to the reduction of the durability of the parts.

Table 1 shows the results of measuring the axial residual stresses in the surface layers of steel 45 having the electroerosive coating of copper and CEC of copper + chromium, as well as the SPD effects on the magnitude and sign of these stresses.

Processing steel 45 with the use of the EEA method performed by copper (electrode) results in the formation of the tensile stress with the value of the depth of occurrence up to 0.1 mm in the surface layer and having its maximum value up to 170 MPa on the surface. Applying the CEC of copper + chromium onto steel 45 results in increasing the values both of the stress and the depth of occurrence, respectively, up to 210 MPa and 0.15 mm.

As a result of the BSRG strengthening of the samples after the EEA process by Cu and Cu + Cr, the deformation curves significantly change, because the deformation values have negative sign, which fact determines the presence of the favorable compressive stresses in the surface layer.

Table 1. The results of measuring the value, sign and depth of the residual stresses in the surface layer of steel 45 after the EEA and SPD processes.

Strengthening	Residual Stresses, σ, MPa	Depth Occurrence, h, mm	Roughness, Ra, μm
EEA			
EEA by Cr	250	0.2	3.5 – 4.6
EEA by Cu	170	0.1	0.6 – 1.0
EEA by Cu + Cr	210	0.15	0.6 – 0.7
EEA + SPD			
EEA by Cr + SPD	- 520	0.9	0.5
SPD + EEA by Cr + SPD	- 550	0.8	0.5
EEA by Cu + SPD	- 200	0.2	0.1
EEA by Cu + Cr + SPD	-350	0.4	0.1

The residual stresses occurring in the surface layers of the parts are inextricably linked to such an operational characteristic as fatigue strength.

When testing the field shafts with the CEC of Cu + Cr, it was found that, as a result of using the EEA method, the fatigue strength was 1.5 times decreased (from 395 to 255 MPa) in comparison with the uncoated samples, but it was 1.5 times higher than for the samples, which were only alloyed with chromium. The ball-running (BSRG) process of the CEC of Cu + Cr increased their fatigue strength by 16-20% in comparison with their basic version, namely, the uncoated samples (Figure 1)

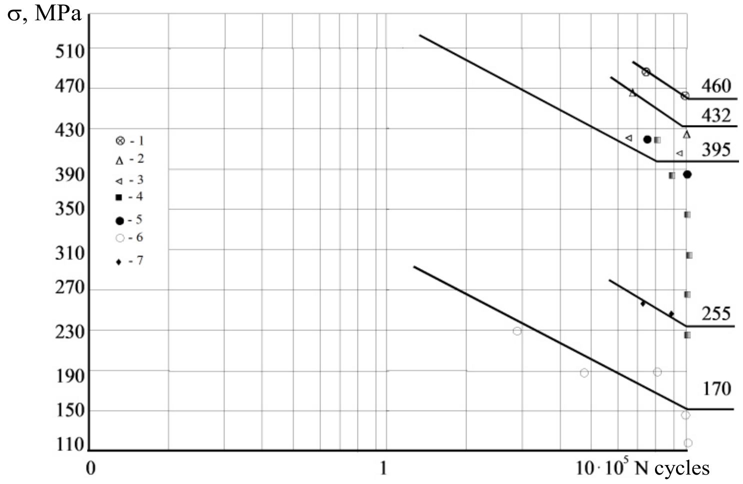

Figure 1. The fatigue strength values for the field samples made of steel 45 after EEA and SPD methods: 1. The EEA method by (Cu + Cr) + BSRG; 2. The EEA method by Cr + DS; 3. The EEA method by Cu + BSRG; 4. Without strengthening; 5. The EEA method by Cr + by Cr + DS; 3. The EEA method by Cu + BSRG; 6. The EEA method by Cr; 7 The EEA method by (Cu + Cr).

Increasing the fatigue strength values for the field shafts through the application of the CEC and the subsequent SPD processes is primarily due to decreasing the levels of the residual stresses thereof. In addition, increasing the fatigue strength is facilitated by the structure of the CEC coatings. Thus, having arisen on the surface of the shaft and growing down, a microcrack develops deeper and "bumps" into the CEC soft component and then it temporarily "damps" (relaxes), thereby increasing the fatigue strength of the shaft.

The analysis of Figure 1 shows that the fatigue strength of the field samples coated with a soft antifriction metal copper and subsequently processed using the SPD method is at the level of the uncoated samples, therefore, if necessary, the above said complex of strengthening technologies can be recommended for practical application.

Since the areas of the destructions of all the samples strengthened by the SPD method are located outside the coatings, increasing the fatigue strength values are even greater.

The wear results for the samples strengthened by the EEA + SPD methods and those without strengthening were compared with the results of the analysis of the samples strengthened by the method of pneumatic and centrifugal processing with the use of a ball ∅12, 7 mm and by the method of breaking – in with a roller ∅76 mm that were obtained at the Lubrication and Wear-Resistant Coating Laboratory, JSC "NPAO" VNIIcompressormash, Sumy, Ukraine [6].

It should be noted that after pneumatic and centrifugal processing with the use of a ball ∅12,7 mm and breaking – in with a roller ∅76 mm the microhardness of the surface layer was 270 and 305 HV, respectively.

In compliance with the obtained data, there were plotted the graphs demonstrating the friction coefficients changes, depending on the type of strengthening method and the test period of time (Figure 2). The results of measuring both the linear (Δh) and integral (Δm) wear rates of the samples are listed in Table 2.

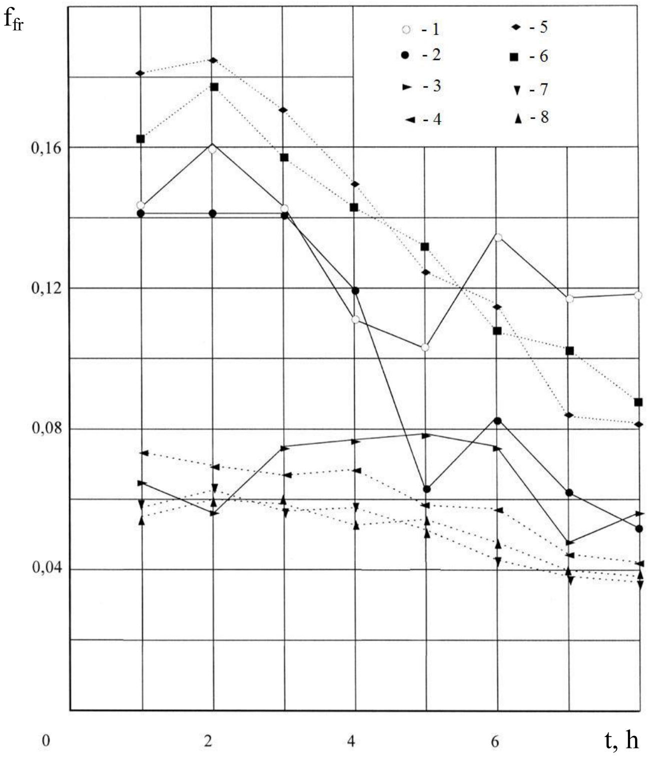

Figure 2. Changing the friction coefficient of steel 40XH on Babbitt depending on the type of strengthening and the interaction period time at: 1 - grinding; 2- pneumatic and centrifugal strengthening; 3 – breaking-in with a roller; 4 – The EEA method by Cr + Diamond Smoothing (DS); 5 – The EEA method by W + DS; 6 –The EEA method by VK8 + DS; 7 - Cu + the EEA method by VK8 + BSRG; 8 – The EEAA method by VK8 + BSRG + the EEA method by Cu + EEA method by VK8 + BSRG.

Table 2. Wear of strengthened steel 40HN paired with Babbitt B-83.

Strengthening	Wear	
	Weight wear x10 ^{3}, kg	Linear wear, μm
No strengthening	0.079	6.516
	0.081	6.501
	0.077	6.509
Pneumatic and centrifugal strengthening with the ball of ∅12,7	*	3.0**
Breaking-in with the roller of ∅76,0	*	2.0**
The EEA method by Cr + DS	0.023	2.043
	0.027	2.067
	0.022	2.003
The EEA method by W + DS	0.0039	2.507
	0.042	2.605
	0.040	2.489
The EEA method by VK8 + DS	0.035	2.322
	0.033	2.420
	0.034	2.303
The EEA method by (Cu + W) + BSRG	0.019	1.255
	0.017	1.204
	0.018	1.311
The EEA method by (Cu + VK8) + BSRG.	0.016	1.017
	0.015	1.104
	0.014	1.005
The EEA method by VK8 + BSRG + the EEA method by (Cu + VK8) + BSRG.	0.012	0.821
	0.010	0.826
	0.012	0.819

* - no data; ** - the data are taken from [6].

As a result of the SPD treatment (pneumatic and centrifugal strengthening, breaking-in by a roller), the coefficient of friction of the unstrengthened samples made of steel 40XH decreases by 1.5 - 2.0 times. With the combined strengthening process of EEA + SPD, the friction coefficient of the chrome coating is minimal, and for the EEA method by the hard alloy of VK8 it is maximal.

The use of copper as a pre-coating sharply reduces not only the roughness, but also the friction coefficient of the CEC being formed. Thus, with subsequent alloying by a hard alloy VK8, the copper, which was applied as a first layer, melts, fills the irregularities and pores of the coating, and covers it with a thin copper film that ultimately results in decreasing of the coefficient of friction.

Fig. 3 shows the nature of the change in the linear wear values of the samples made of 40HN steel strengthened by the method of EEA + SPD under condition when the hard alloy of VK8 with and without a sublayer of copper was used as the electrode alloying material. In the first approximation, the wear resistance curves resemble exponentially increasing relationships. All the samples initially expose more intensive wear, which after two hours of abrasion slows down and becomes more stable. The best wear resistance is possessed by the samples made of 40HN steel strengthened in the following sequence: the EEA method by VK8 + BSRG + the EEA method by Cu + the EEA method by VK8 + BSRG. In this case, the first and the last layers of the hard alloy of VK8 were applied at Wu = 0.2 J, and the intermediate (copper) layer was applied at Wu = 0.08 J. The BSRG process was produced after applying the first layer and the last one.

It should be noted that when a precoating of a soft antifriction material is used, it is most expedient to apply as the SPD method the BSRG or DS processes performed by the smoothing devices with R ≥

3 mm, otherwise the DS process results in "enveloping" of a soft material (in this case copper) on a diamond indenter, and, as a result, reducing the quality of the layer being formed.

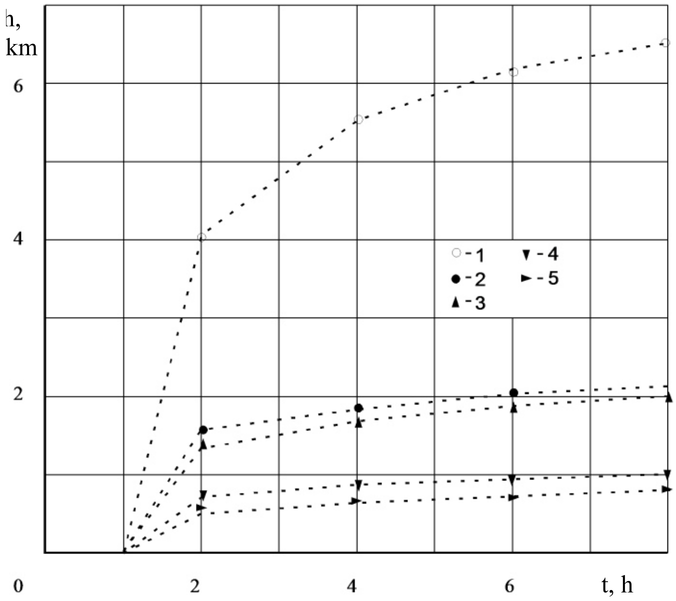

Figure 3. The nature of wear of steel 40HN working in tandem with Babbitt B-83: 1 - grinding; 2 - the EEA method by VK8 + DS; 3 - the EEA method by Cr + DS; 4 - the EEA method by (Cu + VK8) + BSRG; 5 - the EEA method by VK8 + BSRG + the EEA method by (Cu + VK8) + BSRG.

Earlier [7], it was established that to determine the wear equation constants for both the weight equation (1) and the linear one (2), it is necessary to approximate the experimental wear data for a given pair and the nature of the interaction of rubbing surfaces.

$$\Delta m = \Delta m_s \cdot e^{-E_A / A_{fr}} \tag{1}$$

where

Δm is weight wear;

Δm_s is saturation weight wear, i.e. the maximum permissible wear during the period of stable wear;

E_A is wear process activation energy;

A_{fr} is work done by friction.

$$\Delta h = \Delta h_s \cdot r_s / r \cdot e^{-E_A / A_{fr}} \tag{2}$$

where

Δh is linear wear;

Δh_s is a linear wear of saturation;

r, r_s are respectively, density of the surface layer during the period of stable wear and the same at the onset of the saturation wear, i.e., the wear for the greatest depth obtained during the period of stable wear Δh_s.

The results of the work done by friction at testing the samples made of steel 40HN, strengthened by the EEL and PPD methods and tested on the friction machine of CMC-2 according to the disk-pad scheme, wherein Babbitt B-83 was used as a pad material, are presented in Table 3. In addition, Table 3 shows the averaged values of the friction coefficients of f_{fr} for the samples of 40HN steel subjected to different types of strengthening operations (see Figure 3).

Table 3. Results of calculating a friction work value A_{fr} per 1 hour of the testing process.

Type of strengthening	Friction coefficient f_{fr}	A_{fr} per 1h, J	$1/A_{fr}$, $J^{-1} \times 10^{6}$
Without strengthening	0.12	336960	2.968
The EEA method by Cr + DS	0.06	168480	5.935
The EEA method by W + DS	0.14	393120	2.544
The EEA method by VK8 + DS	0.13	365040	2.739
The EEA method by Cu + the EEA method by VK8 + BSRG	0.05	140400	7.123
The EEA method by VK8 + BSRG + the EEA method by (Cu + VK8) + BSRG	0.05	140400	7.123

$$A_{fr} = f_{fr} \cdot P \cdot V \cdot t, \tag{3}$$

Where f_{fr} is a coefficient of friction for a sample of steel 40HN subjected to various types of strengthening; P is load acting onto the pad; V is a sliding velocity; T is a test time of 1 hour (3600 s).

To build a graph of relationship between $\ln\Delta m$ and A_{fr}^{-1}, it is necessary to determine the weight wear values of the samples at different values of friction work, i.e., at different periods of wear-out failure time (Table 4), and then to plot the curves of the relationships between $\ln\Delta m$ and A_{fr}^{-1} for the samples subjected to various types of strengthening (Figure 4). All the data necessary for this procedure are listed in Table 5.

Table 4. Relationships between the values of the weight wear Δm, as well as the values being inverse ones to the values of the friction work A_{fr}^{-1}, and test periods of time.

Type of strengthening	Test time t, h						
	1	2	3	4	5	6	7
	Weight wear Δm, kg x 10^{5} Value being inverse to value of the friction work $1/A_{fr} \times 10^{6}$, J^{-1}						
Without strengthening	2.8 2.968	5.1 1.484	6.2 0.989	7.0 0.742	7.5 0.594	7.7 0.495	7.9 0.424
The EEA method by Cr + DS	0.8 5.935	1.5 2.968	1.8 1.978	2.0 1.484	2.15 1.187	2.2 0.989	2.3 0.848
The EEA method by W + DS	1.4 2.544	2.5 1.272	3.0 0.848	3.4 0.636	3.65 0.509	3.8 0.424	3.9 0.363
The EEA method by VK8+ DS	1.3 2.739	2.4 1.370	3.0 0.913	3.3 0.685	3.5 0.548	3.55 0.457	3.6 0.391
The EEA method by Cu + the EEA method by VK8+ + BSRG	0.60 7.123	1.2 3.561	1.3 2.374	1.45 1.780	1.65 1.425	1.75 1.187	1.85 1.018
EEA method by VK8+ + BSRG +the EEA method by (Cu + VK8)+ BSRG	0.4 7.123	0.77 3.561	0.95 2.374	1.05 1.780	1.13 1.425	1.16 1.187	1.2 1.018

Table 5. Relationships between the logarithms of the weight wear Δm and the test time at abrading of the steel 40HN samples on Babbitt B-83.

Type of strengthening	Test time t, h						
	1	2	3	4	5	6	7
	Logarithm of weight wear Δm						
Without strengthening	-10.48	-9.48	-9.68	-9.57	-9.49	-9.47	-9.45
The EEA method by Cr + DS	-11.74	-11.10	-10.92	-10.82	-10.75	-10.72	-10.68
The EEA method by W + DS	-11.18	-10.60	-10.41	-10.30	-10.22	-10.18	-10.15
The EEA method by VK8+ DS	-11.25	-10.64	-10.41	-10.32	-10.26	-10.25	-10.23
The EEA method by Cu + the EEA method by VK8 + BSRG	-12.02	-11.33	-11.25	-11.14	-11.01	-10.95	-10.89
The EEA method by VK8+ BSRG +the EEA method by (Cu + VK8)+ BSRG	-12.43	-11.77	-11,56	-11.46	-11.39	-11.36	-11.33

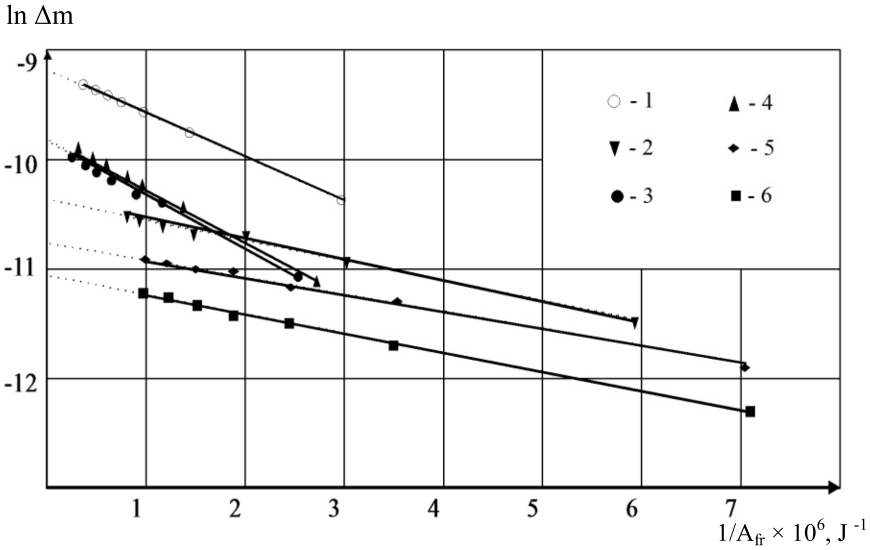

Figure 4. Relationships between the logarithm of the weight wear and the value being inverse to the value of the friction work for samples subjected various types of strengthening: 1 - without strengthening, 2 – the EEA method by Cr + DS, 3 – the EEA method by W +DS, 4 - the EEA method by VK8 + DS, 5 - the EEA method by (Cu + VK8) + BSRG, 6 - the EEA method by VK8 + BSRG + the EEA method by (Cu + VK8) + BSRG.

The tangent values of the slopes of the straight lines to the abscissa axis are listed in Table. 6. According to the wear equation $E_A = |\text{tg}\ \alpha|$.

The pre-exponential factor is obtained by the segment cut off on the ordinate axis of the straight line extended to the abscissa value of $A_{fr}^{-1} = 0$ ($\ln\Delta m = \ln\Delta m_s$ and at $A_{fr}^{-1} \to 0$).

The results of calculating the value of the wear process activation energy determined in two ways, that is, at $E_A = A_{fr}$ and at $E_A = |\text{tg}\alpha|$, correspondingly, and also the value of the saturation weight wear of Δm_s, are listed in Table 6.

Table 6. Calculation of the weight wear constant of E_A and the value of the weight wear saturation Δm_s.

Type of strengthening	$E_A = \lvert tg\,\alpha \rvert$, J	$E_A = A_{fr}$, J	%	$\Delta m_s x\ 10^5$, kg
Without strengthening	421160	434780	3.2	9.5
The EEA method by Cr + DS	205560	204080	0.7	2.7
The EEA method by W + DS	455970	443160	2.9	4.5
The EEA method by VK8+ DS	452720	443160	1.2	4.5
The EEA method by Cu + the EEA method by VK8 + BSRG	158641	160227	1.0	1.9
The EEA method by VK8+ BSRG +the EEA method by (Cu + VK8)+ BSRG	154429	156900	1.6	1.4

Some incompatibility (0.7 ... 3.2%) of the values of the wear-weight constants, that is, the values of activation energies, which were determined by different methods, can be explained as a result of various measurement errors. On the whole, the convergence of the results is satisfactory.

To build a relationship between the linear wear logarithm and the value being inverse to the friction work value, it is necessary to measure the linear wear values at the various values being inverse to the friction work values (Table 7).

The graphs of the relationships between the values of $\ln\Delta h$ and A_{fr}^{-1} for the samples made of 40HN steel treated with the various types of strengthening are shown in Figure 5. All the data that are necessary for building the graphs are given in Table 8. In addition, Table 8 shows a value of a density of an abradable layer as a function of a linear wear amount.

As it can be seen from Table 8, under the above said wear conditions, the surfaces of the test samples are subjected to a relatively uniform wear, and the values of density of the abradable surfaces insignificantly varies (2.5 ... 4.9%), which is most likely a consequence of errors in measuring both the weight wear and the linear one. Therefore, $r_s \sim r$.

It follows that the linear wear equation (2) takes the form:

$$\Delta h = \Delta h_s \cdot e^{-E_A/A_{fr}} \tag{4}$$

Table 7. Relationship between the value of linear wear Δh, as well as the value being inverse one to the value of friction work A_{fr}^{-1}, and the test time.

Type of strengthening	Test time t, h						
	1	2	3	4	5	6	7
	Weight wear Δh, µm Value being inverse to value of the friction work $1/A_{fr}\ x\ 10^6$, J^{-1}						
Without strengthening	2.32 2.968	4.15 1.484	4.90 0.989	5.60 0.742	5.95 0.594	6.30 0.495	6.50 0.424
The EEA method by Cr + DS	0.71 5.935	1.3 2.968	1.6 1.978	1.77 1.484	1.87 1.187	1.94 0.989	2.0 0.848
The EEA method by W + DS	0.89 2.544	1.65 1.272	1.95 0.848	2.15 0.636	2.30 0.509	2.40 0.424	2.50 0.363
The EEA method by VK8+ DS	0.82 2.739	1.57 1.370	1.87 0.913	2.07 0.685	2.20 0.548	2.25 0.457	2.30 0.391
The EEA method by Cu + the EEA method by VK8 + BSRG	0.37 7.123	0.67 3.561	0.80 2.374	0.87 1.780	0.95 1.425	1.1 1.187	1.2 1.018
The EEA method by VK8+ BSRG +the EEA method by (Cu + VK8)+ BSRG	0.28 7.123	0.54 3.561	0.65 2.374	0.74 1.780	0.78 1.425	0.79 1.187	0.82 1.018

Table 8. Relationship between the logarithm of the value of linear wear Δh, as well as the value of the surface layer density, and the test time.

Type of strengthening	Test time t, h						
	1	2	3	4	5	6	7
	Logarithm of the value of linear wear Δh Value of the surface layer density r x10^{-3}, kg/m^3						
Without strengthening	0.84 7.70	1.42 7.82	1.58 8.05	1.72 7.96	1.78 8.02	1.84 7.78	1.87 7.74
The EEA method by Cr + DS	-0.34 7.18	0.26 7.35	0.47 7.17	0.57 7.20	0.63 7.32	0.66 7.22	0.69 7.32
The EEA method by W + DS	-0.12 10.02	0.5 9.65	0.67 9.80	0.77 10.08	0.83 10.11	0.90 10.08	0.92 9.94
The EEA method by VK8+ DS	-0.20 10.09	0.45 9.74	0.62 10.22	0.72 10.15	0.78 10.10	0.81 10.04	0.83 9.97
The EEA method by Cu + the EEA method by VK8 + BSRG	-0.99 10.32	-0.50 10.4	-0.32 10.35	-0.24 10.24	-0.05 10.06	0.12 10.07	0.182 10.67
The EEA method by VK8+ BSRG +the EEA method by (Cu + VK8)+ BSRG	-1.27 9.10	-0.62 9.08	-0.43 9.31	-0.30 9.04	-0.25 9.23	-0.23 9.35	-0.20 9.32

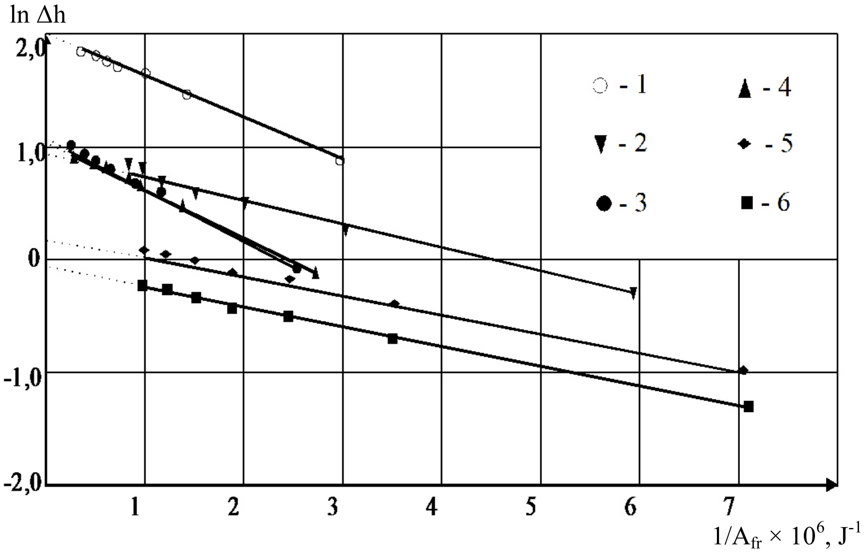

Figure 5. Relationships between the values of lnΔh and the values of A_{fr}^{-1} for samples subjected various types of strengthening: 1 - without strengthening, 2 – the EEA method by Cr + DS, 3 – the EEA method by W +DS, 4 - the EEA method by VK8 + DS, 5 - the EEA method by (Cu + VK8) + BSRG, 6 - the EEA method by VK8 + BSRG + the EEA method by (Cu + VK8) + BSRG.

The tangent values of the slopes of the straight lines to the abscissa axis are listed in Table 9. The pre-exponential factor is obtained by the segment cut off on the ordinate axis of the straight line extended (extrapolated) to the abscissa value of $A_{fr}^{-1} = 0$ ($\ln\Delta m = \ln\Delta m_s$ and at $A_{fr}^{-1} \to 0$).

The results of calculating the value of the wear process activation energy(the linear wear constant) E_A determined in two ways, that is, at $E_A = A_{fr}$ and at $E_A = |tg\alpha|$, correspondingly, and also the pre-exponential factor (saturation wear Δh_s) are listed in Table 9.

Table 9. Calculation of the wear constant of EA and the value of linear wear of saturation Δh_s).

Type of strengthening	$E_A = \|tg\,\alpha\|$, J	$E_A = A_{fr}$, J	%	Δh_s, μm
Without strengthening	407680	416670	2.2	7.8
The EEA method by Cr + DS	208930	203200	2.8	2.45
The EEA method by W + DS	467760	460950	1.5	2.9
The EEA method by VK8+ DS	456370	452160	0.9	2.85
The EEA method by Cu + the EEA method by VK8 + BSRG	164257	165407	0.7	1.16
The EEA method by VK8 + BSRG +the EEA method by (Cu + VK8)+ BSRG	150022	150969	0.5	0.98

Some incompatibility (0.5 ... 2.8%) of the values of the activation energies for the process of linear wear, which were determined by various methods, can be considered as results of various measurement errors. On the whole, the convergence of the results is satisfactory.

Since the processes of reducing the weights of the samples Δm (weight wear) and also the sizes of the samples along the depths of their surface layers Δh (linear wear) proceed simultaneously and are the derivatives of a common process, that is, a wear-out, then the activation energy (the wear constant) should be uniform, namely, $E_{\Delta m}$ must be equal to $E_{\Delta h}$.

In Table 10, there are shown the summarized values of energies to provide for activation of the weight and linear processes of wear, respectively, $E_{\Delta m}$ and $E_{\Delta h}$, as well as the values of the weight and linear processes of wear of saturation, respectively, Δm_s и Δh_s. In addition, Table 10 shows the data of the density of the surface layers worn down to the values of saturation wear.

It should be noted that, when carrying out the comparative tests for wear resistance of the samples with various kinds of the electroerosive coatings, the linear wear should be given the preference, since the weight wear cannot provide objective results because of the different values of density of abradable coatings.

Table 10. Summary of the wear equation constants for abrading the samples of steel 40HN on Babbitt B-83.

Type of strengthening	$E_{\Delta m}$, J	$E_{\Delta h}$, J	%	Δm_s x 10^5, kg	Δh_s, μm	R_s x10^{-3}, kg/m^3
Without strengthening	427970	412180	3.83	9.5	7.8	7.76
The EEA method by Cr + DS	204820	206070	0.61	2.7	2.45	7.02
The EEA method by W + DS	449570	464360	3.28	4.5	2.9	9.88
The EEA method by VK8+ DS	455460	454270	0.26	4.5	2.85	10.06
The EEA method by Cu + the EEA method by VK8 + BSRG	159434	164832	3.4	1.9	1.16	10.43
The EEA method by VK8 + BSRG +the EEA method by (Cu + VK8)+ BSRG	155665	150496	3.4	1.4	0.98	9.10

Using the above mentioned technique, it is possible to determine the constants of the wear equation, and therefore, envisage any wear for any material of a friction pair.

4. Conclusions

1. The use of combined electroerosive coatings (CEC), which are formed by alternately applying copper and chromium on steel 45, reduces the tensile stresses and the depth of their propagation in comparison with the coatings only made of chromium, respectively, of 250 to 210 MPa and of 0.2 to 0.15 mm. The use of the surface plastic deformation (ball-rolling) (SPD) results in changing the sign of deformation from the positive sign to the negative one, which fact witnesses about the availability of the favorable compressive stresses in the surface layer

2. The values of fatigue strength of the CEC, which are formed by alternately applying copper and chromium, are 50% higher than those of coatings only consisting of chromium. The SPD process increases the fatigue strength of the combined electroerosive coatings (CEC) made of Cu + Cr by 20% as compared to the base version, namely, the sample having no coating.

3. There has been developed and implemented a new combined technology to strengthen and repair the shaft-type parts. On combining the EEA and SPD methods, this technology consists in the formation of the surface layers having specified operational properties.

4. There have been set the criteria for evaluating alternative variants of the combined EEA technologies and for providing the choice of the most rational variants thereof. There has been developed the technique for determining wear constants, namely, the values of energy for activating wear processes for various materials of friction pairs, as well as for specifying the wear equation constants, namely, for the weight wear and / or the linear wear of saturation. All these approaches allow predicting the most reliable choice of the technology that is expedient to improve the quality of the surface layer of a product.

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