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Ultrasonic layer-by-layer treatment of PN85Y15 coating as a way to increase wear resistance of friction pair with bronze

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ABSTRACT

Tribotechnical tests on wear resistance of friction pairs "coating PN85Y15 - bronze BrB_2", at loads of 100 and 300 N, sample rotation speed of 300 rpm, with lubricant Lukoil Luxe 5W40 have been carried out. It is shown that the plasma coating applied to steel 45 together with layer-by-layer ultrasonic treatment (UST) with the power of 200 W, in comparison with the coating with UST with the power of 400 W and without UST, had a higher adhesion to the base metal and sufficient porosity, which working with lubricant provided the crankshaft with increased lubricity, formation of favourable compressive residual stresses, formation in the coating of a two-component structure of large (~40 μm) granules and small (~1–7 μm) superhard intermetallic particles of phases Fe_2Al_5, which filled surface imperfections and reduced the coating roughness by 2 times, reduced the friction coefficient by 2 times, weight wear by 12 times and contact temperature by an average of 5 °C.

KEYWORDS

plasma spraying • tribotechnical tests • ultrasonic treatment • surface roughness • friction coefficient contact temperature

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Introduction

The main operational characteristic of internal combustion engines (ICE) is the wear resistance of crankshafts, because as a result of changes in the size, shape and mutual arrangement of parts due to shaft wear, the initial clearance between friction pairs is broken, which leads to the rupture of the lubricating layer, pressure drop in the system, as well as the appearance of knocking, overheating and de-strengthening of the material of parts in the engine [1–5].

At present, the most widespread application for manufacturing and restoration of crankshafts are wear-resistant iron-based coatings applied by plasma spraying. Such coatings have increased hardness, brittleness and reduced thermal conductivity due to oxide inclusions and pores. Plasma spraying units Plasma coatings are characterised by a flaky, layered structure with high heterogeneity of physical and mechanical properties due to the developed surface of joints between particles and the increased content of oxide inclusions [6–10]. Plasma spraying units do not require significant initial investments, and easily converted to the production of powders from a variety of materials [11].

To eliminate the mentioned drawbacks the authors in the previous work in the friction pair "coating - cast iron" [12–14] applied simultaneously with plasma spraying of PN85Y15 powder particles, layer-by-layer ultrasonic treatment (UST) with 200 and 400 W power.

During the operation of crankshafts, the main defect leading to the loss of their serviceability is the wear of main and connecting rod journals paired with a piston bronze ring (liner) working with lubricant [15–31].

Therefore, the purpose of this work was to increase the wear resistance of friction pair "plasma coating - bronze", due to layer-by-layer ultrasonic treatment combined with plasma spraying of ferromagnetic powder PN85Y15.

Materials and Methods

Tribotechnical tests with synthetic grease Lukoil Luxe 5W40 were carried out on the friction machine SMTS-2 (Fig. 1), according to the scheme "Roller - Roller" with the rotation frequency of the lower roller 300 rpm, with the load on the fixed upper roller 100 and 300 N, test time 2 hours.

Fig. 1. External view of friction machine SMC-2

The following characteristics of the "coating - bronze" tribocouple were determined: torque and a friction coefficient, weight wear, contact temperature and surface roughness of the specimens before and after the test. In order to achieve measurement accuracy, each test was carried out three times.

The lower rotating roller (Fig. 2(a)) was made of antifriction beryllium bronze of BrB_2 grade (97-98 % Cu and 2 % Be, up to 0.5 % Ni). The upper, fixed rollers were fitted with inserts (Fig. 2(b)) cut from blanks (Fig. 2(c)) of 45 steel and coated with plasma sprayed PN85Y15 (84%Ni, 15%Al, 0.2%Fe) nickel-based powder (84%Ni, 15%Al, 0.2%Fe) (Fig. 2d)) without UST and with simultaneous 200 and 400 W layer-by-layer UST.

A portable profilometer - Mahr Surf PS-1 profilograph was used to assess surface roughness. Metallographic studies were carried out using a μVizo-MET reflected light microimager. The phase composition of the coatings was studied with the help of X-ray structure analyser, and residual stresses were measured with the help of resistive electro-contact method of non-destructive testing on the SITON-TEST device. Micro-X-ray spectral analysis (study of the concentration distribution of elements in the coating) was performed on a Camebax micro analyser equipped with an INCA ENERGY 350 energy dispersive spectrometer at a probe electron energy of 15 keV.

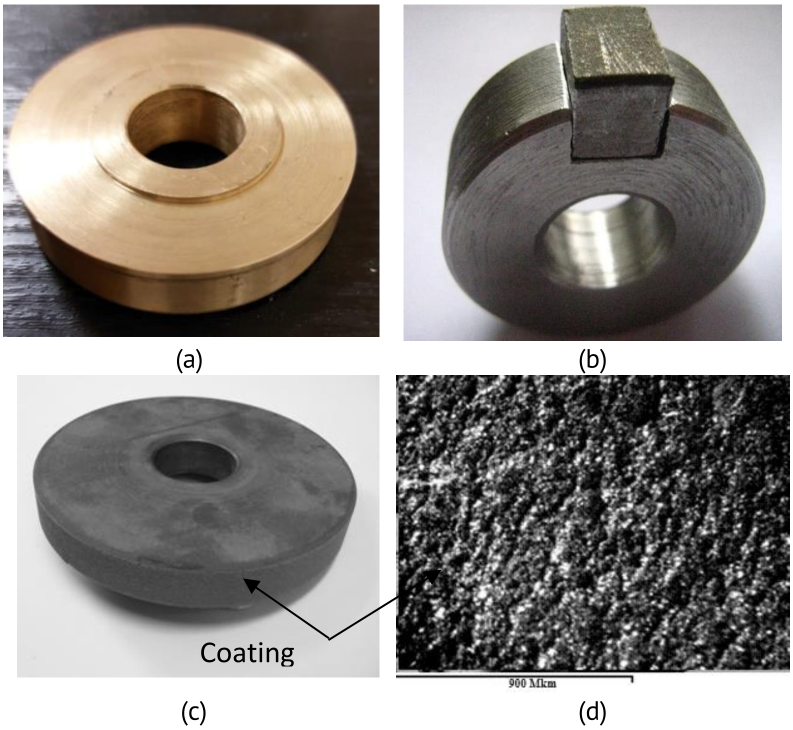

Fig. 2. The images of specimens: (a) lower roller made of bronze BrB_2; (b) upper roller with coated steel 45 insert; coated billet (c,d) for cutting out inserts and testing on the SMC-2 friction machine

Results and Discussion

Metallographic and micro-X-ray spectral studies of the coating structure

As can be seen from Fig. 3(a,b), a loose and adhesion-unstable coating without UST with a thickness of ~ 116 μm made of large molten particles of 28–100 μm was formed. The plasma PN85Y15 powder coating applied together with a 200 W layer-by-layer UST (Fig. 3(c,d)) with a thickness of ~ 82 μm had good adhesion to the base metal (steel 45) and was formed from two types of particles, probably with different temperature interval of their formation: large particles of 25–70 μm and small particles of 1–7 μm, which filled uneven areas.

With increasing the power of layer-by-layer UST up to 400 W, only large molten particles of 18–40 μm size were observed, which formed a coating of different thicknesses on average ~ 46 μm (Fig. 3(e,f), having good adhesion to the base metal.

Figure 4 shows the results of micro-X-ray spectral study of the distribution of chemical elements (Ni, Al, Fe) before and after ultrasonic treatment (UST) with 200 W power in coatings deposited on steel 45 samples by plasma spraying of PN85Y15 powder. As can be seen from Fig. 4(a), if PN85Y15 powder particles are sputtered without UST a loose and adhesionally unstable coating with a thickness of ~ 120 μm is formed. Iron from steel 45 and nickel and aluminium from the coating mutually diffuse towards each other to form a transition layer (Fig. 4(b)), which could be responsible for the adhesion strength of the coating. As can be seen from Fig. 4(b), at a distance from the surface of ~ 100 μm, there is a sharp decrease in the content of all elements in the coating, which could lead to a drop in strength and the formation of a boundary crack.

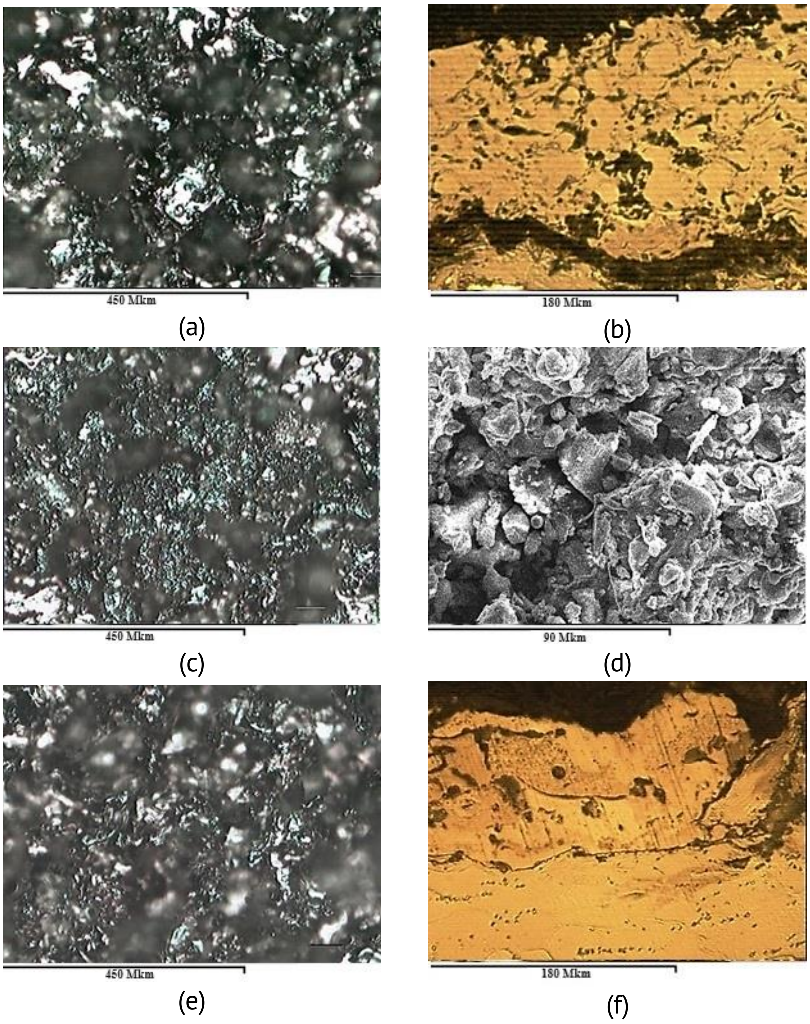

Fig. 3. Metallographic images of the surface of PN85Y15 coatings of samples from steel 45 (a,c,d,e) and their cross sections (b,f) (without UST (a,b) and with UST power 400 W (e,f), 200 W (c,d))

Figure 4(c) shows a ferromagnetic powder coating obtained using a 200 W UST. In the border zone, at a distance from the surface ~ 60 μm (Fig. 4(d)), in the coating there was a sharp decrease in the content of Ni, Al and simultaneous transition from steel 45 elements Fe and Cr, which provided the coating with good adhesion to the base metal.

A characteristic feature of ultrasound is that, unlike thermal energy, acoustic energy affects plasma chemical reactions of liquid chemical elements, activates physical and chemical processes and is absorbed by the boundaries of grains, particles and the boundaries of the transition layer between the coating and the substrate.

It can be assumed that during magnetisation of coatings made of ferromagnetic materials (e.g., nickel, iron) magnetic moments of domains acquire preferential orientation in the direction of the external magnetic field and the coating material deforms (expands or contracts) even before solidification (crystallisation). Probably, magnetostrictive deformation of liquid phase particles reduces the crystallisation temperature and promotes the formation of ultrafine and superhard particles of Fe_2Al_5 phases with the size of 1–7 μm after layer-by-layer UST with 200 W power.

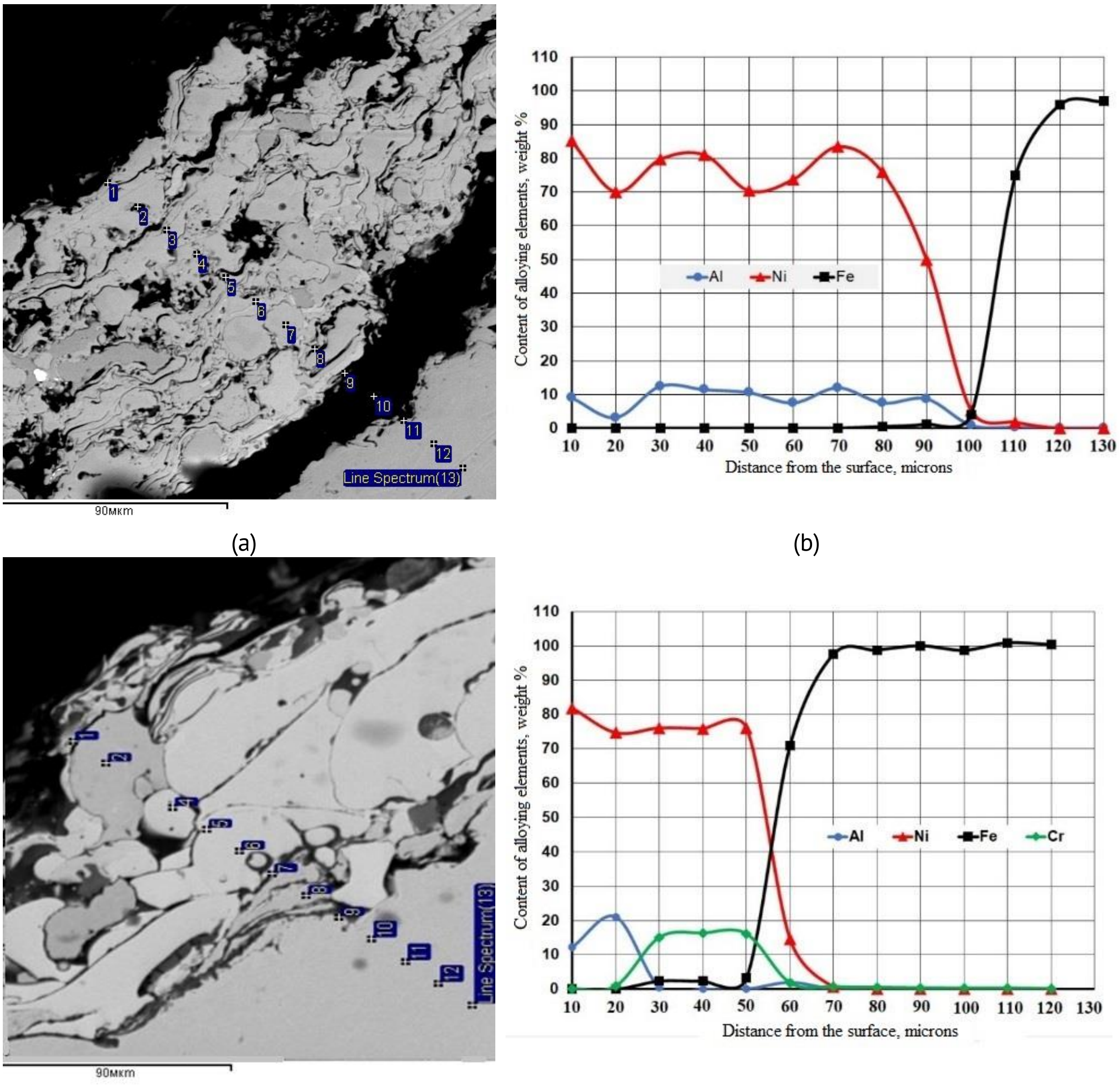

Fig. 4. Metallographic images of the surface of PN85Y15 coatings of steel 45 samples (a,c) and concentration distribution of elements (b,d) in the coating without UST (a,b) and with 200 W UST (c,d)

According to the Fe-Al equilibrium diagram [32], at the eutectic temperature of 654 °C, the solubility of iron in aluminium is negligible (0.03 at. %), while the solubility of aluminum in iron is 600 times higher and amounts to about 32 %.

As shown in Fig. 4(d), after layer-by-layer UST with 200 W, unlike the coating without UST, iron from steel 45 and aluminium from the coating mutually diffuse towards each other to form a transition layer in which aluminium dissolves into iron to form ultrafine particles Fe_2Al_5 (71 at. % Al).

At room temperature, the particles of intermetallic phase Fe_2Al_5 have a high hardness of 11.5 GPa. The appearance of such particles in the surface layer may explain the high wear resistance of the coating after layer-by-layer UST with 200 W power.

It should be noted that after layer-by-layer UST with 200 W power, in the transition layer of the coating, in which aluminium dissolves in iron and particles Fe_2Al_5 are formed, chromium with a maximum concentration of 16.35 % diffuses there from steel 45 (Fig. 4(d)), which should potentially increase the corrosion resistance of such a coating.

X-ray diffraction studies of phases and internal stresses of coatings

The results of the X-ray diffraction study of the phase composition of the coatings deposited on steel 45 samples by plasma spraying of PN85Y15 powder, without UST and with 200 W UST, are substituted in Table 1.

In the coating treated with UST power of 200 W, in comparison with the coating without UST treatment, in addition to large particles of nickel-based compounds Ni_3Al [11,33], small particles of the second phase Fe_2 Al_5 were detected (Fig. 3(c,d), Table 1). At the same time, diffraction lines of Ni_3 Al compounds on the basis of nickel were significantly broadened, which indicated the appearance of significant internal stresses in the coating.

Table 1. X-ray diffraction studies of phases and internal stresses of coatings

Coating grade	Spray coating mode with UST	Phase composition of the coating	At a distance from the surface *h*, μm					
			20	120	220	320	420	520
			Residual stress values, MPa					
PN85Y15	Without UST	Ni_3 Al	- 18	+ 13	+ 14	+ 18	+ 20	+ 22
PN85Y15	UST 200 W	Ni_3 Al, Fe_2Al_5	- 118	- 72	- 70	- 62	- 50	- 48

As shown by the results of residual stress measurement using the SITON-TEST device, favourable compressive stresses appeared in the coating treated with a 200 W UST (Table 1). This could contribute not only to the surface hardening but also to the adhesion strength and wear resistance of the coating.

Tribotechnical studies of coatings

Figures 5 and 6 show the results of time variation of the coefficient of friction (K_{tr}) during a wear test of friction pair "coating PN85Y15 - bronze BrB_2" at the 100 and 300 N loads: before and after layer-by-layer UST of 200 and 400 W. It can be seen that the coefficient of friction of the friction pair "coating with UST-200 - bronze" decreased by 2 times (from 0.6 to 0.3) at a 100 N load in comparison with the coating without UST.

Figures 7 and 8 show the results of temperature variation in time during testing of friction pair "PN85Y15 coating - BrB2 bronze": before and after layer-by-layer UST with 200 and 400 W power at 100 and 300 N loads.

During the 100 and 300 N load tests, the coatings obtained by a 200 W layer-by-layer UST had a lower mean operating temperature in comparison with coatings without UST: 7 °C (67.7 and 60.7) and 6.3 °C (77.3 and 71.0), respectively.

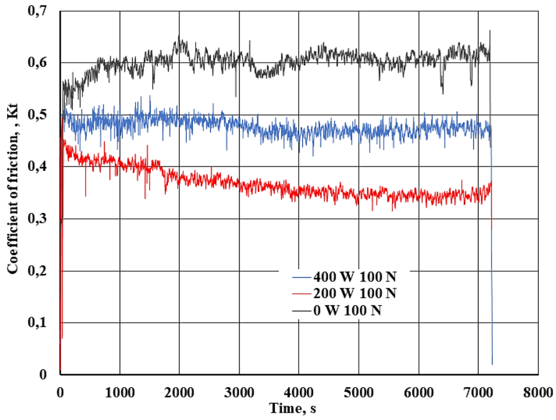

Fig. 5. Variation of friction coefficient during 2-hour test "PN85Y15 coating - BrB2 bronze" at a load of 100 N

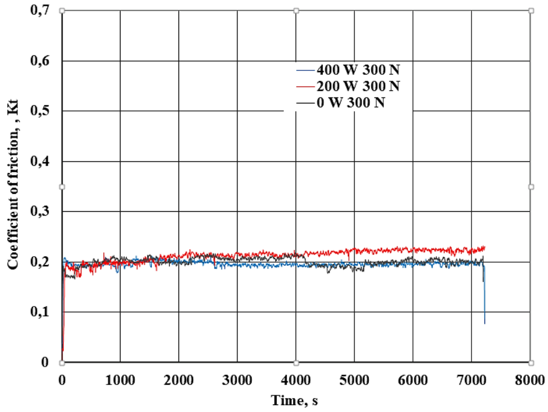

Fig. 6. Variation of friction coefficient during 2-hour test of friction pair "PN85Y15 coating - bronze BrB2" at a load of 300 N

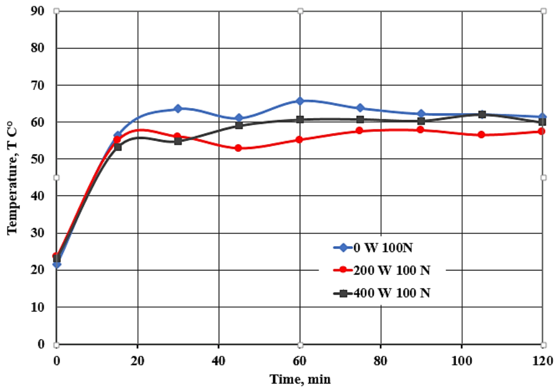

Fig. 7. Temperature change during a 2-hour test of the friction pair "PN85Y15 coating - BrB_2 bronze" at a load of 100 N

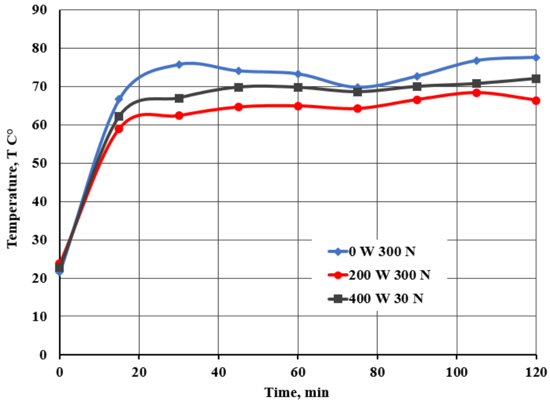

Fig. 8: Temperature change during a 2-hour test of the friction pair "PN85Y15 coating - BrB_2 bronze" at a load of 300 N

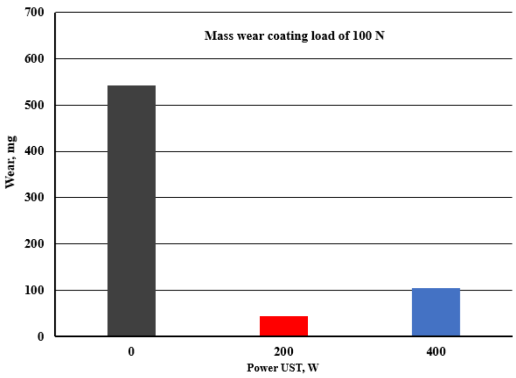

Fig. 9. Mass wear of the PN85Y15 coating after testing at a load of 100 N: before and after 200 W and 400 W layer-by-layer USTs

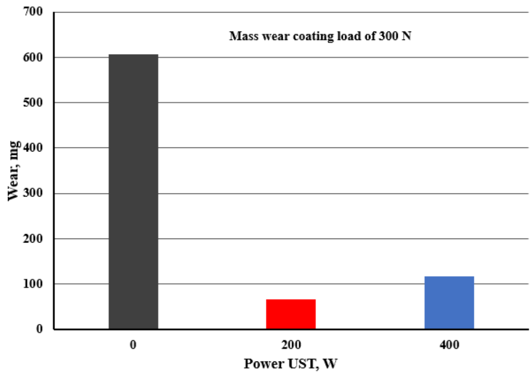

Fig. 10. Mass wear of PN85Y15 coating after tests at 300 N load: before and after layer-by-layer UST of 200 W and 400 W power

Table 2 shows the mass wear results of the PN85Y15 coating after a 2-hour 100 and 300 N load tests before and after 200 and 400 W layer-by-layer UST.

Table 2. Mass wear of the coating after testing at 100 and 300 N load

Coating grade	Spray coating mode with UST	Load 100 N	Load 300 N
		Wear, mg	Wear, mg
PN85Y15	Without UST	542.67	605.67
PN85Y15	**UST 200 W**	**44.67**	**66.5**
PN85Y15	UST 400 W	104.67	116.67

At the 100 and 300 N load tests, the coatings obtained by plasma spraying of PN85Y15 powder combined with 200 W layer-by-layer UST had less wear in comparison with the coating without UST by more than 12 times (542.67 and 44.67 and more than 9 times (605.67 and 66.67), respectively.

Profilometric studies of the coating structure

The optical microscopy results completely coincides with the profilometric studies of the structure of the coating surfaces (see Table 3).

Table 3. Roughness parameters of PN85Y15 coatings paired with bronze after the 100 and 300 N load tests: before and after layer-by-layer UST with 200 and 400 W power

Spray coating mode with UST	Load 100 N			Load 300 N		
	Ra	*Rz*	*Rq*	*Ra*	*Rz*	*Rq*
Without UST	7.402	37.423	9.214	7.078	32.828	8.695
UST 200 W	**3.182**	**18.331**	**4.082**	**4.203**	**22.260**	**5.231**
UST 400 W	3.931	29.375	4.960	4.119	21.435	5.200

Table 4. Roughness parameters of coatings characterising wear resistance and sprayed before and after USTs of 200 W and 400 W (R_{PK} is a parameter characterising the height of protrusions that wear quickly during the first run-in period; R_K is the depth of surface profile irregularities defining the profile base, bearing area as the outer layers wear; R_{VK} is the average depth of profile depressions that determine the lubricity of the surface; R_{PK}+R_K are the sum of parameters characterising wearability of working surfaces of the product, e.g. crankshaft journals)

Coating grade	Spray coating mode with UST	R_{pk}	R_k	R_{vk}	$R_{pk}+R_k$
PN85Y15	Without UST	48	35	17	83
PN85Y15	UST 200 W	**40**	**55**	**5**	**95**
PN85Y15	UST 400 W	46	46	8	92

Roughness parameters of powder coating sprayed with layer-by-layer UST of 200 W power are an arithmetic mean profile deviation R_a, height of profile irregularities at ten points R_z, mean square deviation of profile R_q decreased by 2 times in comparison with coating without UST. The roughness parameters characterising the wear resistance of the powder coating sprayed with layer-by-layer UST of 200 W power (R_{pk}, R_k, R_{vk}) were also improved. These parameters were obtained from the construction of the surface reference curve (Abbott curve), which characterises the percentage of material content by roughness layer height within the maximum (R_{max}) and minimum height (R_{min}) of microroughnesses. Four parameters characterising the wear process were determined from the Abbott curve (Table 4).

As can be seen Fig. 11, the coatings obtained by plasma spraying of PN85Y15 powder combined with layer-by-layer UST with a power of 200 W, had a better complex of parameters characterising the wear process in comparison with the coating without UST (Table 4).

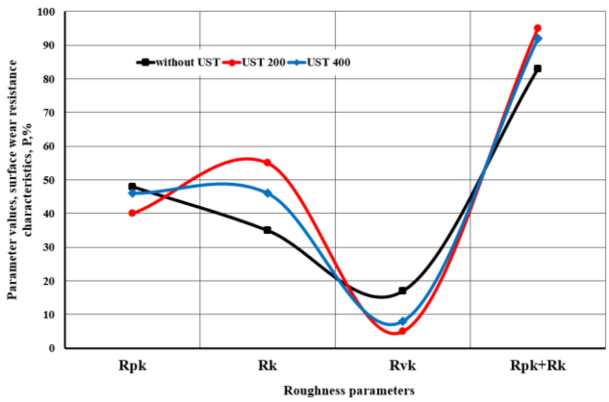

Fig. 11. Values of surface roughness parameters R_{pk}, R_k, R_{vk} characterising wear resistance of PN85Y15 coatings in the surface layer

Based on the obtained results, it can be concluded that the coatings obtained by plasma spraying of ferromagnetic powder combined with layer-by-layer UST had higher adhesion to the base metal in comparison with the coating without UST, and sufficient porosity, which provided the crankshaft with increased lubricity if working with lubricant.

In addition, the coatings obtained by layer-by-layer UST with 200 W power formed a two-component structure of large (~ 40 μm) and small (~ 1–7 μm)of granules, which filled the surface imperfections and provided the crankshaft not only with increased lubricity, but also with adhesive strength.

Conclusions

Based on the results obtained, it can be concluded that the coatings obtained by plasma spraying of PN85Y15 ferromagnetic powder combined with layer-by-layer UST of 200 W, compared to the coating without UST, possessed:

1. higher adhesion to the base metal and sufficient porosity which, when working with the lubricant, will provide the crankshaft with increased lubricity;
2. two-component structure of granules - large (~ 40 μm) and small (~1–7 μm), which filled surface imperfections and reduced coating roughness by 2 times;
3. structural-phase transformations with the formation of ultrafine superhard intermetallic particles of Fe_2Al_5;
4. formation of favourable compressive residual stresses;
5. improvement of tribotechnical properties of friction pair "coating - bronze": reduction of wear in 12 and 9 times, at load 100 and 300 N, respectively; reduction of friction coefficient in 2 times and contact temperature on average by 5 °C.

Thus, based on the results obtained, it can be concluded that plasma spraying of PN85Y15 powder with layer-by-layer UST with a power of 200 W leads to an increase in the wear resistance of surfaces in comparison with coating without UST. Such coating is recommended for spraying on worn main and connecting rod journals of crankshafts of internal combustion engines of automobiles.

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