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Tribology Study of High-Technological Composite Coatings Applied Using High Velocity Oxy-Fuel

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Abstract: In the work are studied the differential parameters of wear and wear resistance of high-tech composite coatings of powder superalloys with nickel matrix, WC-12Co and mixed compositions. Coatings were created and applied to a substrate of steel with a different flame velocity - 700 m/s and 1000 m/s without preheating the substrate and with preheating the substrate to 650^{o} C. The wear is carried out with a "thumb-disk" tribotester under dry surface friction with fixed black corundum abrasive particles. Comparative results were obtained for the microstructure and texture of the pre- and post- friction coating, the porosity, roughness, hardness, the dependence of mass wear, the speed and wear intensity and the wear resistance of the coatings on the number of friction cycles. Influence of the flame rate and substrate temperature on wear resistance and differential wear parameters has been determined.

Keywords: tribology, wear-resistance, coatings, HVOF

1. Introduction

The main task of the tribology is to increase the operating resource of the contact joints and work bodies in the machines by reducing the friction and wear of the contact surfaces. One of the modern methods for reducing the wear of the parts operating under extreme operating conditions - abrasion, erosion, corrosion, impact and vibration loads, vacuum and others, is associated with the application of HighVelocity Oxy-Fuel (HVOF) method [1÷9].

HVOF is a modern tribotechnology for obtaining high-tech composite coatings on surfaces in various areas of transport and industry: various types of transport, mining equipment, energy, gas and oil extraction, road machinery and others.

The essence of the HVOF method consists in the impact interaction between powder particles moving at supersonic velocity into a flame jet and the surface of the substrate on which the coating is deposited [1,3,6÷11].

Fuel (kerosene, acetylene, propylene and hydrogen) and oxygen are fed into a combustion chamber where the hot flame with a temperature > 3000°C flows under high pressure through a nozzle at supersonic speed. The powder composition is supplied axially in the combustion chamber under high pressure or in the nozzle in the side where the pressure is lower (Figure 1).

Powder compositions known in the literature as powder super alloys are micronized particle mixtures of various metals, alloys, ceramics, polymeric materials. The particles carried by the flame stream pass into a plastic and/or semi-plastic state in the form of a particle or a drop and after contact with the substrate due to the high kinetic energy they deform to form thin lamellae with different shape. When struck with irregularities, the droplet particles are cooled, forming adhesive and cohesive contact links with the base surface and with each other forming a laminar structure of the composite coating [12÷14].

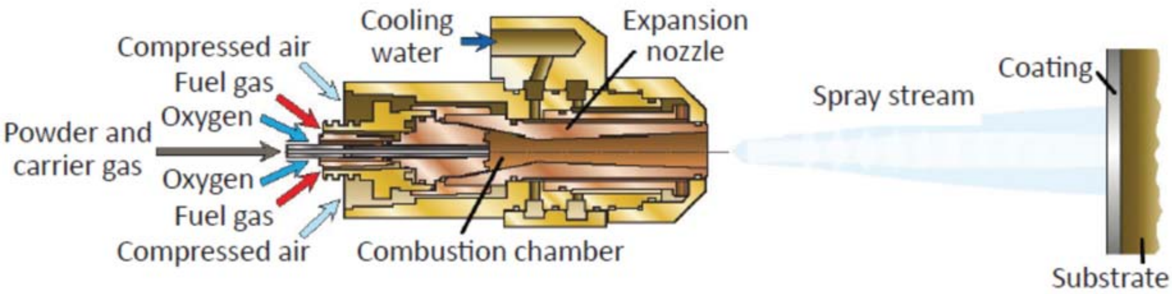

Figure 1. Schematic drawing of the high velocity oxygen fuel spraying (HVOF) process with gas-fuel gun (Reproduced by permission of Oerlikon Metco).

Gas-flame based coatings applied by the HVOF method are characterized by high adhesion hardiness/resiliency and low porosity due to the large kinetic energy of the particles. The extremely short contact time of the particles with oxygen from the environment creates favourable conditions for the absence of oxides in the coating, which in turn is of great importance for the wear resistance. As opposed to sonic gas-flame coatings, the HVOF method does not preheat the base surface to a high temperature, avoiding thermal deformations, and this makes it applicable to a number of responsible details in the industry. Certain research by the authors suggests that the combination of surface preheating and supersonic gas spray (HVOF method) leads to an increase of the wear resistance of coatings coated using powder compositions with lower hardness [13÷18].
The aim of the present study is to investigate the influence of three factors: particle velocity in the flame jet, preliminary heat treatment of the substrate and the presence of WC-12Co particles on the wear parameters of coatings applied with the 602P powder composition and HVOF method at the same surface abrasion conditions of rigidly bonded abrasive particles.

2. Experimental details

2.1. Materials and deposition conditions

Five types of HVOF (High Velocity Oxy-fuel) coatings were investigated. The coatings have been deposited on support (substrate) of one and the same material of chemical composition, represented in Table 1. The hardness of the substrate varies within the limits 193.6 ÷ 219.5 HV.

Table 1. Chemical composition (wt. %) of the coated material (medium-carbon steel substrate).

Element	C	Si	Mn	Ni	P	S	Cr	Fe
Percentage	0.4	0.2	0.55	0.3	0.45	0.045	0.3	Balance

The preliminary preparation of the substrate prior to the deposition of the coatings includes three stages: decontamination, blasting (erosion) and mechanical treatment.

The decontamination is done using lubricants and solvents, which remove the deposited mechanical components, moisture and organic molecules, adsorbed by the surface. Their extraction from the depth of the surface layer is accomplished by blazing in flame, i.e. increase of the temperature („sweating" of the surface) or by vapour-streaming device and once again purifying using solvents.

The blasting represents erosion of the surface by means of a system having definite technical parameters. The abrasive material "Grit" is used in accordance with the requirements of the standard ISO 11126 with granulomere composition of the abrasive in mm as percent ratio as follows: 3.15 ÷ 1.4 mm – 9.32%; 1.63 ÷ 0.5 mm – 16.4%; 1.4 ÷ 1.0 mm – 15.8%; 1.0 ÷ 0.63 mm – 39.6%; 0.5 ÷ 0.315 mm – 9.32%; 0.315 ÷ 0.16 mm – 9.32%; particles of size below 0.15 mm different fractions – up to 100% of the following chemical compounds: SiO_2 – 41% , combined in the form of silicates; AlO – 8.3%, MgO – 6.6%, CaO – 5.5% and MnO – 0.4%. The technical parameters of the mobile system for blasting are: input pressure 0.8 MPa; operating pressure in the nozzle – 0.4 MPa; diameter of the nozzle ϕ – 7 mm; distance between the nozzle and the surface – 30 mm; angle of interaction of the stream with the surface – 90^o.

The coatings have been deposited applying a system model MICROJET POWDER using a set of technological parameters, listed in Table 2.

Table 2. Technological regime parameters for HVOF coating deposition.

№	**Parameter**	**Technological regime**	
1	Fuel/oxygen (C_3H_8/O_2) ratio, %	45/100	55/100
2	Particle velocity, m/s	700	1000
3	Spraying distance, mm	100	
4	Impact angle, grad	90	
5	Air pressure, MPa	0.5	
6	Nitrogen pressure, MPa	0.4	
7	Powder feed rate, g/min	22	

The coatings are applied with metal powdered compositions of nickel and tungsten. The designations and chemical composition of the coatings are presented in Table 3.

Table 3. Coating designation and appropriate powder chemical composition (wt. %)

Sample	**Coating designation**	**Powder chemical composition, wt. %**
1	602P:700	Cr: 14.5; Si: 4.61; B: 2.85; Fe: 4.42; Co: 0.05;
2	602P:700: PHS*	Cu: 2.65 ; Mn: 3.2
3	602P:1000	**Ni: Balance**
4	WC–12Co:1000	Co: 12; C: 5.4; Fe: < 0.1; Ni: < 0.1; **W: Balance**
5	602P/ WC–12Co:1000	1 : 1

With powder composition 602P, three types of coatings are obtained: Coating 602P: 700 – at particles velocity in the flame stream - 700 m/s without pre-heat treatment of the substrate; Coating 602P: 700: PHS * at a 700 m/s particle velocity in the flame stream with pre-heat treatment of the substrate in a thermal chamber at 650° C for 3 hours and a 602P: 1000 coating at 1000 m/s particle velocity in the flam stream without pre-heating the substrate.

Two types of coatings are obtained with a tungsten-based powder mixture: a WC-12Co: 1000 coating is applied at a particles speed of 1000 m/s and a 602P/WC-12Co: 1000 coating obtained by mixing the two powdered compositions 602P and WC-12Co in a ratio of 1:1. The average particle size range is 40÷45 ± 2.5 μm obtained by agglomeration process with the sintering.

Table 4 gives details of the thickness, porosity, roughness and hardness of tested coatings.

Table 4. As-deposited thickness, porosity, roughness and hardness of tested coatings.

Sample	Coating designation	Thickness μm	Porosity %	Roughness μm	Hardness HRC
1	602P:700	100	4.1	Ra=2,888; Rq=3,456	58-60
2	602P:700: PHS*	100	3.6	Ra=0,168; Rq=0,208	61-64
3	602P:1000	115	2.2	Ra=5,798; Rq=7,298	62-64
4	WC–12Co:1000	115	0.8	Ra=2,148; Rq=2,685	65-67
5	602P/ WC–12Co:1000	115	1.2	Ra=6,659; Rq=8,087	62-66

The roughness (Ra, Rq) of the coatings is measured with a TESA Rugosurf 10-10G profile meter (Figure 2) in two perpendicular directions.

Figure 2. TESA Rugosurf 10G.

Figure 3. Pocket Leptoskop 2021Fe.

The thickness of the coatings is measured with the Pocket Leptoscope 2021 Fe (Fig. 3). Measurements were made at 10 points of the surface and the arithmetic average value was adopted.

2.2 Abrasive wear testing

The abrasive wear of the coatings is investigated with a "thumb-disk" tribotester under dry surface friction with hard-fixed abrasive particles. The functional diagram of the tribotester is presented in Figure 4.

The test specimen with coating (1) is fixed in the bed of the holder (2) placed in the loading head (8). The front surface of the sample (1) contacts the surface of the opponent body (3) fixed hard to the horizontal disc (4). The disc (4) is driven by an electric motor (6) and rotates about its vertical center axis with a constant angular velocity ω. The normal load P is applied to the center of gravity of the contact site between the sample and the surface and is set with a lever system in the loading head (8).

The friction path is set by the number of cycles with the tachometer 7.The device allows the sliding speed to vary from 0.55 m/s to 1 m s by varying the distance R between the axis of rotation of the disc (4) and the axis of the sample (1).

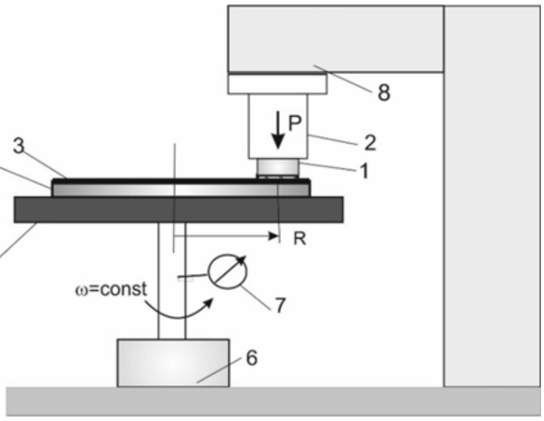

Figure 4. Schematic diagram of abrasive wear testing on pin-disc tribometer

The samples have a cylindrical shape with a diameter of 10 mm and a height of 25 mm. The test was carried out under the following constant friction conditions: normal load P = 4.6 N, nominal contact area - Aa = 0.785 cm^2; Sliding speed - V = 0.71 m/s; R = 0.032 m; abrasive surface - Corundum P 320, number of friction cycles - 100, 200, 300, 400. The friction path at N number of friction cycles is calculated by the formula $S = 2\pi RN$.
The wear characteristics test method consists in measuring the mass wear *m* of the samples for a specific friction path S (friction cycles) under constant conditions - load P and glide speed V. The method includes the following sequence: preparation of samples with the same dimensions; measure the mass *m* of the sample before friction with the electronic scale WPS 180 /C /2 to (accuracy 0,1 mg). Before each measurement of the scale the sample is cleaned of mechanical and organic particles, dried with ethyl alcohol to prevent the electrostatic effect. Calculated are the following wear characteristics:
Specific wear (i_s): Represents the ruptured mass of friction from the surface layer for normal load P = 1N per friction path S = 1m and nominal contact area A_a=1 mm^2:

$$i_s = \frac{m}{PSA_a}, \text{ mg/Nm.mm}^2 \quad (1)$$

Specific wear resistance (I_s): Expressed as the reciprocal value of the specific wear:

$$I_s = \frac{1}{i_s} = \frac{PSA_a}{m}, \text{ Nm.mm}^2\text{/mg} \quad (2)$$

Relative wear resistance(W_s): Relationship between the specific wear resistance of the test coating (I_s) and the wear resistance of the substrate (I_b) by equal friction conditions:

$$W_s = I_s/I_b \quad (3)$$

3. Results and discussion

Tables 5, 6, 7 and 8 represent experimental results for mass wear, specific wear, specific wear resistance, and relative wear resistance for test surfaces for four values of the number of friction cycles respectively.

Table 5. Abrasive wear of tested coatings

Sample	Coating designation	Number of cycles (N)			
		100	200	300	400
		Sliding distance, m			
		20	40	60	80
		Mass loss, mg			
1	602P:700	5.0	10.4	14.3	18.2
2	602P:700: PHS*	1.9	2.7	3.6	4.4
3	602P:1000	1.2	3.1	3.9	4.1
4	WC–12Co:1000	0.5	0.8	1.0	1.2
5	602P/ WC–12Co:1000	0.8	1.3	2.0	2.4
6	Substrate: Steel	12.4	16.6	19.8	22.1

Table 6. Abrasive specific wear of tested coatings

Sample	Coating designation	Number of cycles (N)			
		100	200	300	400
		Sliding distance, m			
		20	40	60	80
		Specific wear, $mg.mm^2/Nm$			
1	602P:700	6.9×10^{-4}	7.2×10^{-4}	6.6×10^{-4}	6.3×10^{-4}
2	602P:700: PHS*	2.7×10^{-4}	1.9×10^{-4}	1.7×10^{-4}	1.5×10^{-4}
3	602P:1000	1.7×10^{-4}	2.2×10^{-4}	1.8×10^{-4}	1.4×10^{-4}
4	WC–12Co:1000	0.7×10^{-4}	0.5×10^{-4}	0.3×10^{-4}	0.3×10^{-4}
5	602P/ WC–12Co:1000	1.1×10^{-4}	0.9×10^{-4}	0.9×10^{-4}	0.8×10^{-4}
6	Substrate: Steel	17.2×10^{-4}	11.5×10^{-4}	9.2×10^{-4}	7.6×10^{-4}

Table 7. Abrasive specific wear resistance of tested coatings

Sample	Coating designation	Number of cycles (N)			
		100	200	300	400
		Sliding distance, m			
		20	40	60	80
		Specific wear resistance, $Nm/mg.mm^2$			
1	602P:700	1.4×10^3	1.4×10^3	1.5×10^3	1.6×10^3
2	602P:700: PHS*	3.7×10^3	5.3×10^3	5.9×10^3	6.7×10^3
3	602P:1000	5.9×10^3	4.5×10^3	5.6×10^3	7.1×10^3
4	WC–12Co:1000	14.3×10^3	20×10^3	33.3×10^3	33.3×10^3
5	602P/ WC–12Co:1000	9.0×10^3	11.1×10^3	11.1×10^3	12.5×10^3
6	Substrate: Steel	0.6×10^3	0.9×10^3	0.9×10^3	0.8×10^3

Table 8. Relative wear resistance of tested coatings

Sample	**Coating designation**	**Wear resistance, Nm/mg.mm^2 (N=400)**	**Relative wear resistance (R)**		
			Influence of heat treatment	Influence of particle velocity	Both influence
1	602P:700	1.6 x 10^3	$R_{1,1} = 1$	$R_{1,1} = 1$	$R_{1,6} = 2.0$
2	602P:700: PHS*	6.7 x 10^3	$R_{2,1} = 4.19$	$R_{3,2} = 1.1$	$R_{2,6} = 8.4$
3	602P:1000	7.1 x 10^3	-	$R_{3,1} = 4.44$	$R_{3,6} = 8.9$
4	WC–12Co:1000	33.3 x 10^3	-	-	$R_{4,6} = 41.6$
5	602P/ WC–12Co:1000	12.5 x 10^3	-	-	$R_{5,6} = 15.6$
6	Substrate: Steel	0.8 x 10^3	-	-	$R_{6,6} = 1$

Figures from 5 to 12 show graphically the dependence of the wear from the friction path and diagrams on the influence of heat treatment of the substrate and the particles peed on the wear resistance of the tested coatings.

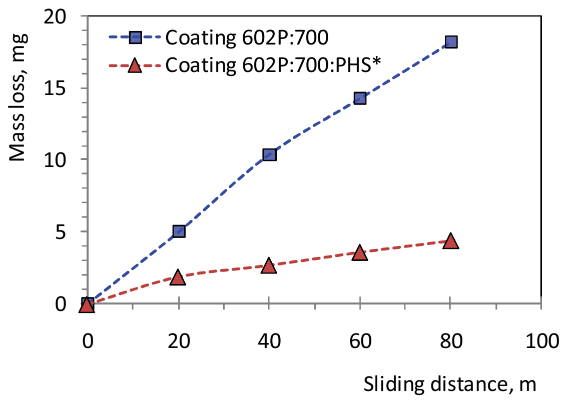

Figure 5. Mass loss vs. sliding distance for coatings on the without and with heat treatment of substrate at particle velocity 700 m/s.

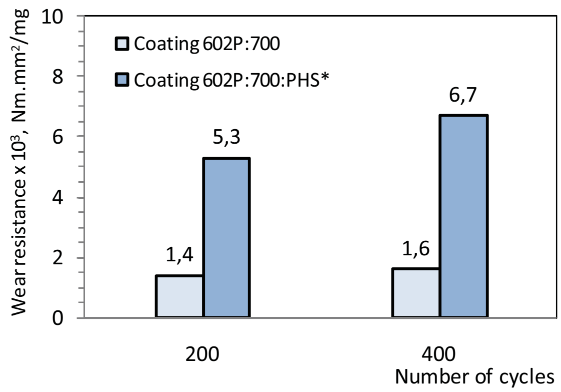

Figure 6. Influence of heat treatment of wear resistance of coatings at particle velocity 700 m/s.

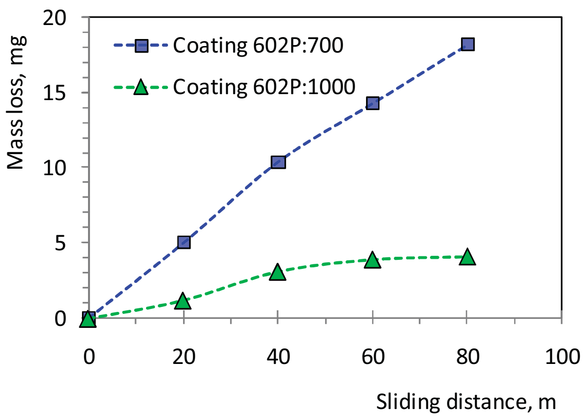

Figure 7. Mass loss vs. sliding distance for coatings at two particle velocity - 700 m/s and 1000 m/s without heat treatment of substrate.

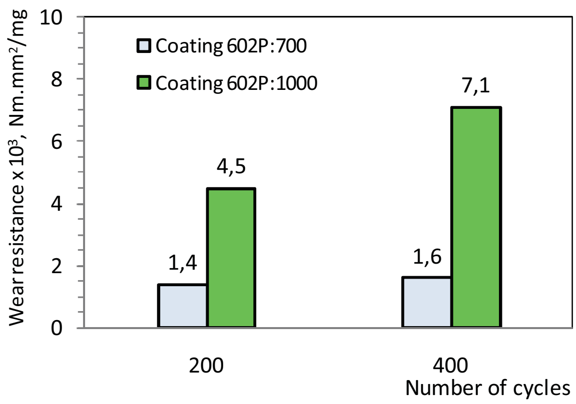

Figure 8. Wear resistance at two particle velocity 700 m/s and 1000 m/s of coatings without heat treatment of substrate.

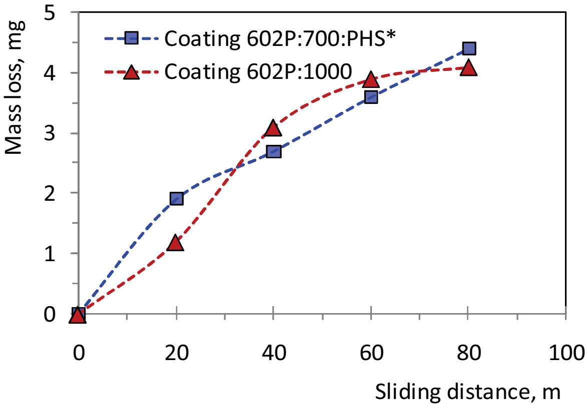

Figure 9. Mass loss vs. sliding distance for coatings at two particle velocity - 700 m/s and 1000 m/s with heat treatment of substrate.

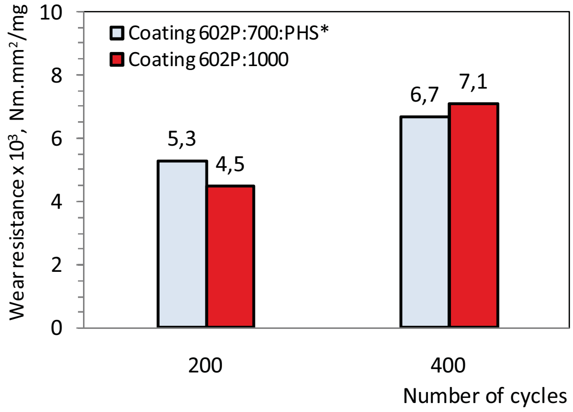

Figure 10. Wear resistance at two particle velocity 700 m/s and 1000 m/s of coatings with heat treatment of substrate.

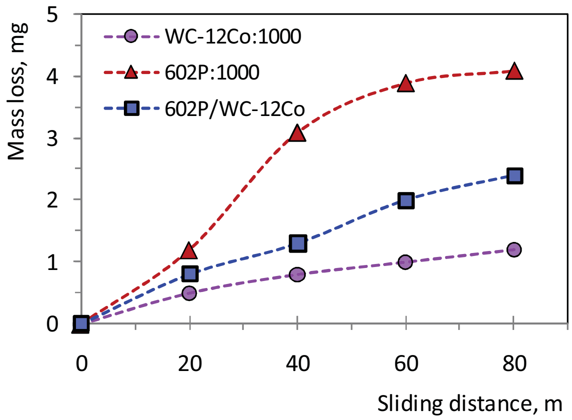

Figure 11. Mass loss vs. sliding distance for coatings 602P, WC-12Co and 602P/WC-12Co without heat treatment of substrate.

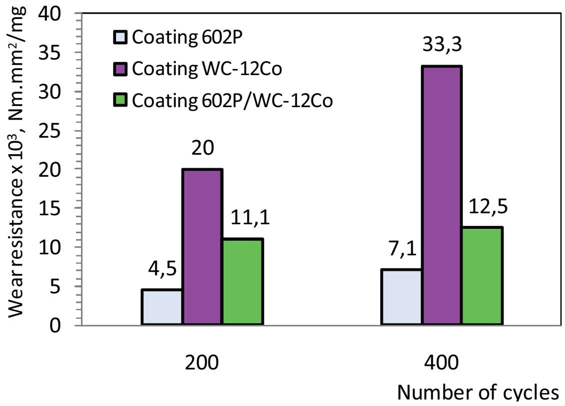

Figure 12. Wear resistance of coatings 602P, WC-12Co and 602P/WC-12Co without heat treatment of substrate.

Figures 13, 14 and 15give the microstructure and morphology of 602P:700 and WC-12Co coatings.

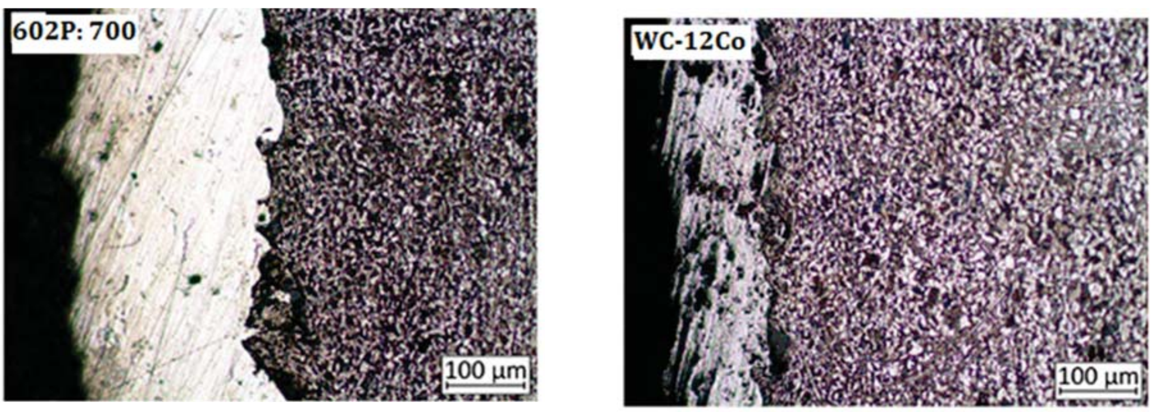

Figure 13. Microstructure properties of 602P:700 and WC-12Co coatings.

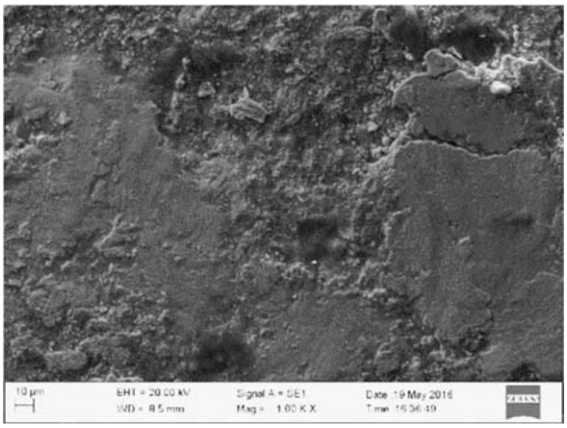

Figure 14. Morphology of 602P:700 coating at 400cycles.

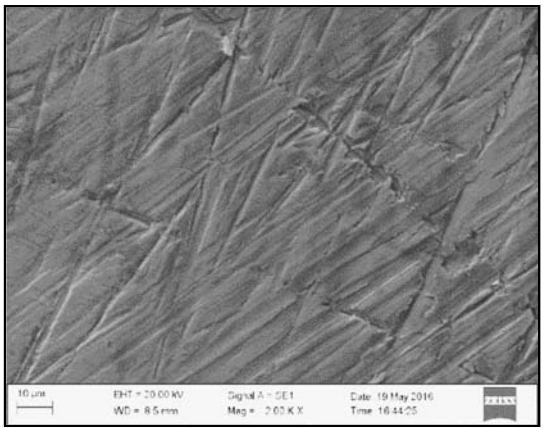

Figure 15. Morphology of 602P:700: PHS*coating at 400 cycles

The analysis of the results of the influence of heat treatment of the substrate and the particle speed on the wear characteristics show the following: In a 602P coating applied at a low supersonic particle velocity (700 m/s) on a pre-heat treated substrate at 650°C for 3 hours, the wear significantly decreases compared to the same coating without heat-heating the substrate. (Figure 5). The wear resistance of such coating increases 3.8 times for 200 cycles and 4.19 times for 400 cycles of friction path (Figure 5, Table 8). The reduction in wear rate and / or wear resistance from the friction path, respectively, is not proportional to the friction path due to the hardening of the coating.

The morphology of the worn coating without heat treatment of the substrate (Figure 14) after 400 cycles of friction is characterized by the presence of irregularly spaced fractal craters. In the surface layer of the worn surface of the heat treatment coating (602P:700:PHS*) the rare traces of the abrasive action of the abrasive particles without the presence of deep deformation (Figure 15). The heat factor influences the adhesion strength and coating density.

The velocity of particle velocity on wear only affects coatings without preliminary heat treatment of the substrate (Figure 7 and Figure 8). A thigh supersonic particle velocity (1000 m/s) the wear decreases, respectively, the wear resistance in creases 4.4 times over 400 cycles of friction path. This is explained by the high density of the coating, i. e. high cohesives trength in the coating volume. The latter is due, on the one hand, to the high kinetic energy of the particles and, on the other hand, to the absence of oxides in the coating.

The latter is the result of the short time of particles stay and their contact with The comparison of the two coatings 602P:700:PHS* and 602P:1000 shows that they have almost the same wear and wear resistance values (Figures 9 and 10).

The results of the new 602P/WC-12Co coating test, which was prepared by mixing a powder of 602P with a 1:1 powder WC-12Co and applied at a particle speed of 1000 m/s, showed that wear abruptly decreased takes twice as low as the 602P: 1000 without WC-12Co. Its wear resistance increases to 2.45 times for 200 cycles and 1.76 times for twice as many cycles (N = 400 cycles).

4. Conclusions

This paper presents results on the influence of particle velocity pre-heat treatment of the substrate and the presence of WC-12C particles on wear and wear resistance of coatings applied with HVOF powder 602P composition under the same surface friction conditions of fixed abrasive particles.

It has been found that the increase in the wear resistance of 602P coating can be achieved in three ways:

- Apply the coating at a particle speed of 700 m/s with pre-heat treatment of the substrate at 650°C for 3 hours. The wear resistance of the coating increases 4.19 times compared to the wear resistance of the coating without heat treatment.
- Apply the coating at a particle speed of 1000 m/s without preheating the surface. The wear resistance of the coating increases 4.44 times against the wear resistance of a coating applied at 700 m/s without heat treatment.
- Powder composition WC-12Co is added to the powder composition 602P in a ratio of 1:1 and the coating is applied at a particle speed of 1000 m/s. The wear resistance of the coating increases 1.76 times in comparison with the wear resistance of a coating applied at 1000 m/s without heat treatment.

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