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Abrasive wear of high velocity oxygen fuel (HVOF) superalloy coatings under vibration load

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Abstract. The present paper considers wear of coatings deposited by HVOF (High velocity oxy-fuel) technology, under conditions of dry friction against abrasive surface accompanied with the action of vibrations perpendicular to the sliding axis. Results are obtained with four type coatings: two types with Ni matrix of composition 602P – without preliminary heating of the basic surface (the substrate) and after substrate heating up to 650°C in a chamber; coating WC-12Co with tungsten matrix and coating obtained by 1:1 proportion powder mixture of both compositions 602P and WC-12Co. Results about the thickness, hardness and coating' morphology are presented, as well as dependences of the wear and the relative wear resistance on vibration speeds in the interval 3.03 to 21.08 mm/s. New results are obtained about the nonlinear relationship between abrasive wear and vibration speed showing minimal wear for all specimens by 6.04 mm/s. It is found that lowest wear shows WC-12Co coating in the entire interval of vibration speed variation: 3.03 to 21.08 mm/s.
The obtained results are new in the literature; they are not presented and published by the authors.

1. Introduction

Modern equipment operates under impact of dynamical load (collision and vibrations) of various intensities.

Mechanical impact and the resulted vibrations involve machine functional characteristics distortion and failures. Variation in vibration parameters influence friction and wear intensity. The strength and wear resistance of materials under vibration conditions are of crucial importance for their functionality and operational resource. Vibration characteristics vary in large interval in the non-stationary operating regime of tractor engines and gas turbines, the variations depending on the stage of wear. Vibration frequency varies from 180 to 6500 Hz, and the amplitude from 0.5 to 10 μm in faulty engines. It is possible that resonance effects emerge in the case of quick change of operation regime, which results in acceleration of fatigue and other wear mechanism [1÷8].

Abrasive wear mostly accompanied by vibration impacts is the basic reason for putting out of normal service of building, agriculture and mining machinery and equipment [5÷7].

One of the ways for improvement of the exploitation resource of technical systems working under conditions of abrasive-vibrational impact is the improvement of surface wear resistance by coating deposition through the HVOF technology.

HVOF (High velocity oxy-fuel) technology is a modern tribotechnology for high wear resistant coatings applied in components, contact joints and surfaces operating under heavy-loaded conditions of abrasion, corrosion, erosion, cavitations, high dynamic loads, vibrations, etc. in transport, mining and power industry, oil and gas industry, road machinery, etc. [7÷25]

HVOF technology for coating deposition consists in impact interaction between the supersonic speed powder particles in the flame stream and the material surface (the substrate) to be coated [10÷17].

The fuel gas (kerosene, acetylene, propylene and hydrogen) and the oxygen are supplied to the combustion chamber, and the flame of temperature higher than 3000°C flows out with high velocity under high pressure though the nozzle. The powder composition is supplied axially under high pressure to the combustion chamber or to the nozzle from the side of the lower pressure (figure1).

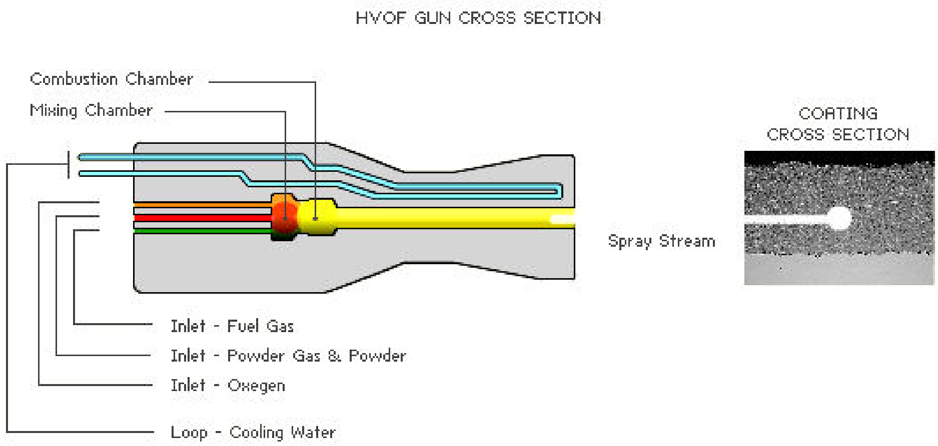


Figure 1. Scheme of the system for coating by HVOF (High velocity oxy-fuel) process.

The powder compositions called also powder super alloys, are mixtures of particles of micrometer size composed of different metals, alloys, ceramics, and polymers. The particles brought by the flame steam change into plastic state in the form of a drop, and after the contact with the substrate deform into thin lamellas. The particles-drops cool at the collision with the roughness forming adhesion and cohesion contact bonds with the substrate surface and between each-other structuring the laminar configuration of the composite coating [13÷22].

The present paper sets out the study on the influence of load vibration speed value upon abrasive wear parameters of HVOF-coatings.

2. Materials and technology

Four kind coatings are studied obtained by the HVOF process technology, which are deposited on a substrate of equal material, namely steel of composition given in table 1. The substrate hardness is between 193.6 and 219.5 HV.

Table 1. Chemical composition (wt. %) of the coated material (substrate).

Element	C	S	Mn	P	Si	Cr	Ni	Fe
Percentage	0.15	0.025	0.8	0.011	0.21	0.30	0.30	Balance

Two type powder mixtures of trade names 602P and WC-12Co are used for the coating deposition; their chemical composition, physical and mechanical properties are given in tables 2 and 3.

The particles are of average size 45 ± 2.5 μm; they are obtained by agglomeration process in clouding sintering.

The coatings are deposited by the system of MICROJET+Hybrid model with technological parameters shown in table 4.

Table 2. Coating 602P.

Chemical composition,wt.%	Melting point, °C	Mohs' hardness
Cr: 13.2	1907	8.5
Si: 3.98	1414	7
B: 2.79	2076	9.5
Fe: 4.6	1538	4
Co: 0.03	1495	5
C: 0.63	3550	-
Ni: balance	1455	4
Surface temperature during the deposition at 120 mm distance: 263°C		
Coating adhesion: 42-43 MPa		

Table 3. Coating WC-12Co.

Chemical composition,wt.%	Melting point, °C	Mohs' hardness
Co: 12	1495	5
C: 2.4	3550	-
Fe < 0.1	1538	4
Ni < 0.1	1455	4
W:balance	3422	7.5
Surface temperature during the deposition at 120 mm distance: 95°C		
Coating adhesion: 63 – 69 MPa		

Table 4. Technological regime parameters for HVOF coating deposition.

№	Parameter	Technological regime
1.	Propylene/oxygen ratio, %	55/100
2.	Jet velocity, m/s	1000
3.	Distance „nozzle-coating" L, mm	120
4.	Angle between orifice axis and surface, α °	90
5.	Air pressure from compressor, bar	5
6.	N_2 pressure in the proportioning device, bar	4
7.	Velocity of powder material feeding, tr/min	1.5
8.	Mass flow rate of the powder material, g/min	22

The following coatings are produced: № 1 – with powder compsition 602P on a substrate without preliminary heating; № 2 – with powder compsition 602P on a substrate with 5 min preliminary heating up to 650°C in a chamber; № 3 – with powder compsition WC-12Co without preliminary heating of the substrate; № 4 – with powder compsition of 1:1 mixture of both compositions 602P and WC-12Co, without preliminary heating of the substrate. After the mechanical treatment all coatings obtain equal thickness of 680 μm.

3. Experimental procedures

Vibro-abrasive wear tests were carried out on the modified pin-on-drum tribometer which is used for abrasive wear tests without vibrations. The tests were performed in the ambient air at room temperature. A schematic diagram of modified pin-on-drum tribometer is presented in figure 2 [4, 6, 7].

Vertical cylindrical specimen (3) with the deposited coating is positioned perpendicular to the impregnated corundum abrasive paper (5) with grain size of (P120 grit). The abrasive paper is fastened to, and supported by a horizontal cylinder (2). The cylinder driven by AC motor (1) rotates with given constant rotational speed about its horizontal axis. Specimen (3) is fixed in the loading head (4) through elastic connection, which allows self-adjustment of the specimen to the abrasive paper (5) and provides possibility for rotation of the specimen around its vertical axis. The loading head (4) engages the static rack bar (7) through the horizontal gear ring (6), providing worm drive and rotation of the specimen around its vertical axis. Static rack bar also provides horizontal movement of the loading head and test specimen (3). In this way a helical wear track is formed. Rotation of the specimen around its vertical axis provides the homogeneous wear in all points of the contact area. Cleaning of the abrasive paper (5) from wear debris is done by an appropriate brush fixed to the loading head (4), together with a vacuum pump.

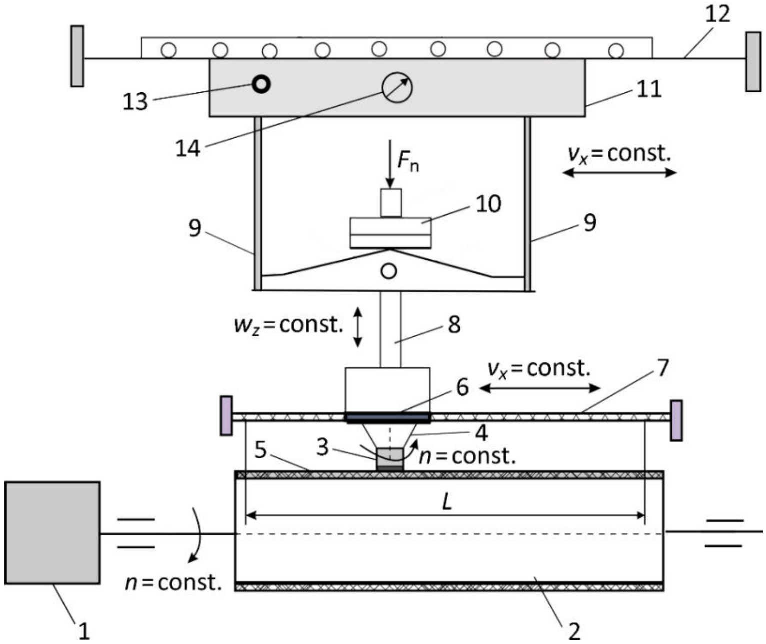
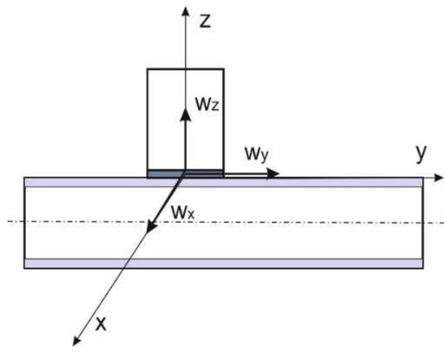


Figure 2. Schematic diagram of vibro-abrasive wear testing on modified pin-on-drum tribometer: 1 – AC motor; 2 – drum (horizontal cylinder); 3 – pin (specimen) with coating; 4 – loading head; 5 – abrasive surface (abrasive paper); 6 – gear ring; 7 – static rack bar; 8 – specimen fastening mechanism; 9 – vibrating frame; 10 – loading weights; 11 – vibrator; 12 – vibrator supporting structure with driving mechanism; 13 – on/off button of the vibrator; 14 – regulator of vibrations parameters.

The vibration parameters: vibration displacement [mm], vibration speed [mm/s] and vibration acceleration [mm/s^2] are measured by the „PCR-VT 204" vibrometer (figure 3 a,b).



(a) (b)

Figure 3. (a) „PCR-VT 204" vibrometer; (b) directions of measured velocity components.

Table 5 shows the vibration components values in three directions: vertical vibration - w_z; vibration in sliding direction - w_y and transversal vibration - w_x in x direction (figure 3b) for each indication of the regulator of vibrations parameters 14 (figure 2).

Table 5. Values of the vibration velocity components and total vibration velocity.

Regulator calibration	1	5	7	9	10
$w_{z,}$ mm/s	3	6	9	16	20
$w_{x,}$ mm/s	0.2	0.35	0.8	3.8	5
$w_{y,}$ mm/s	0.4	0.6	0.9	3.8	4.4
w, mm/s	3.03	6.04	9.08	16.88	21.08

Different values of the vibration speed in the interval 3.03 to 21.08 mm/s are given by means of the vibration regulator. The interval is chosen in accordance to the requirements for assessment and classification of the four groups (K, M, Gand T) machines and equipment in ISO 2372 and VDI 2056.

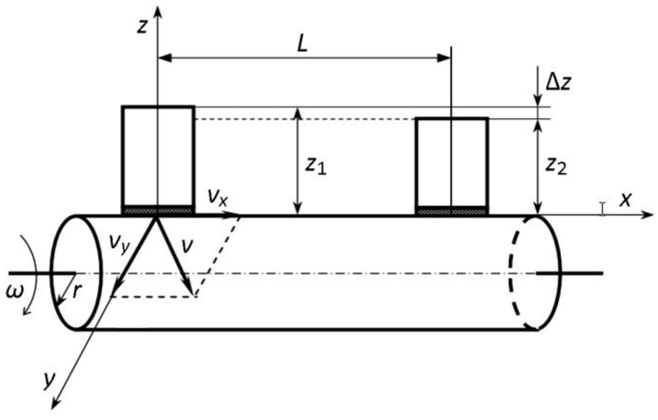


Figure 4. Scheme of the sliding speed of the contact area between the specimen and the rotating cylinder.

The two components V_y and V_x of specimen's sliding speed *V* are determined according to figure 4 by the equations:

$$V_x = \frac{L}{t}\,;\; V_y = r.\omega = r\frac{\pi.n}{30}\,;\; V = \sqrt{V_y^2 + V_x^2} \qquad (1)$$

where: L is the friction way passed by the specimen along the generating line of the cylinder (figure 4). In the conducted experiment experiment L = 0,6 m, passed by the specimen in t = 2,28 min. The cylinder radius is r = 0,075 m, and the revolutions of the cylinder are $n = 40$ rpm. The total friction way on the spiral is calculated by the formula:

$$S = v.t.N \qquad (2)$$

where *N* is the number of sliding cycles. The sliding cycles reveal how many times is passed the friction way L.

Each coated specimen is tested at different vibration speeds in the interval 3.03 to 21.08 mm/s for equal friction conditions. The specimens are of cylindrical form with diameter d = 9 mm, height – 30 mm and of equal contact surface roughness Ra = 0.425 µm.

The study was carried out at constant friction parameters: load 3.92 N (0.4kg), nominal contact area $A_a = 0.64.10^{-4}$ m^2, nominal contact pressure $p_a = 6.12$ N/cm^2, sliding speed v = 0.31 m/s and friction way S = 49.01 m.

The procedure of wear characteristics study consists in measurement of mass wear for each specimen at given constant values of the parameters: load, friction way, sliding speed, abrasive surface type and a given vibration speed. Then a different value of the vibration speed is given under the same sliding conditions, and the mass wear is measured again. The tests are repeated with each specimen for several vibration speed values.

The comparison of the coatings is made based on the parameters: mass wear m, relative wear resistance q_m and vibration factor of the abrasive wear λ_W.

The relative wear resistance is the ratio between friction way S and mass wear m, i.e.

$$q_m = \frac{S}{m}, \text{ [m/mg]} \quad (3)$$

The vibration factor of the abrasion λ_W is dimensionless and is given by the ratio between the specimen's mass wear m_W at the given vibration speed and the mass wear of the same specimen without vibrations - m_o:

$$\lambda_W = \frac{m_W}{m_o} \quad (4)$$

4. Experimental results

Results about the mass wear, the relative wear resistance and the vibration factor of wear are obtained for the studied coatings at different vibration speed values.

Table 6 shows the results for the mass wear of the four type coatings and the base surface at abrasive friction without vibration and five values of the vibration speed in the interval 3.03 to 21.08 mm/s.

Table 7 gives the interval of variation and the average value of coatings hardness before the wear, after the abrasive friction without vibration and after the friction with vibration at vibration speed 21.08 mm/s.

Table 6. Abrasive wear of tested coatings.

№	**Coatings**	**Vibration velocity, mm/s**	0	3.03	6.04	9.08	16.88	21.08
1	602 P	Mass loss, mg	7.2	5.8	4.9	7.2	9.6	11.5
2	602P+HT 650^{o}C	Mass loss, mg	4.6	3.5	2.5	4.8	6.2	7.4
3	WC-12Co	Mass loss, mg	0.5	0.4	0.4	0.5	0.6	0.6
4	602P+WC-12Co1:1	Mass loss, mg	5.5	4.1	3.2	5.6	7.3	8.2
5	coated material	Mass loss, mg	20.6	16.5	12.4	18.5	20.6	25.4

Table 7. Coatings hardness before and after abrasive friction without and with vibration.

№	**Coating**	Hardness before friction, HV	Hardness, HV w = 0 mm/s	Hardness, HV w = 21.08 mm/s
1	602P	168÷196 182	165÷193 179	141÷163 152
2	602P+HT650^{o}C	310÷328 319	301÷325 313	290÷309 300
3	WC-12Co	405÷441 423	398÷432 415	381÷409 395
4	602P+WC-12Co 1:1	480÷508 494	460÷498 479	449÷490 470

Figures 5, 6, 7 and 8 graphically show the mass wear variation with different vibration speeds for all tested coatings and the substrate.

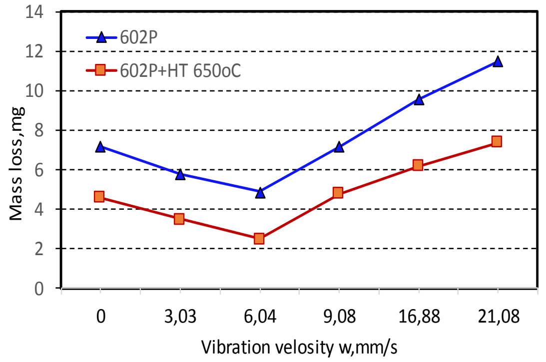


Figure 5. Mass loss variation with the vibration speed for coating 602P without and with preliminary heating of the substrate.

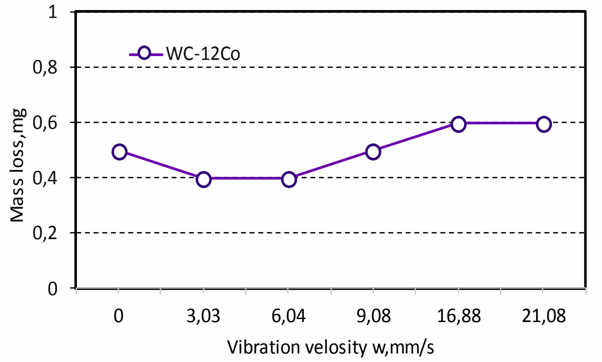


Figure 6. Mass loss variation with the vibration speed for coating WC-12Co without preliminary heating of the substrate.

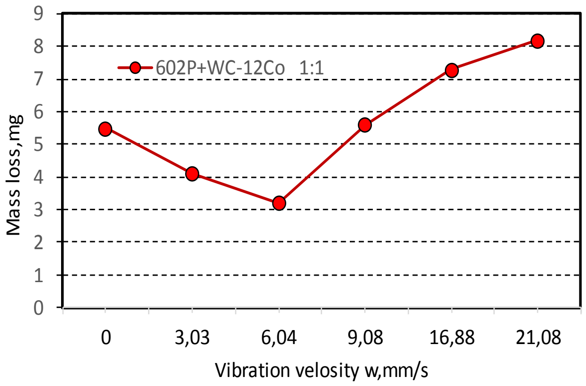


Figure 7. Mass loss variation with the vibration speed for coating 602P+WC-12Co 1:1 without preliminary heating of the substrate.

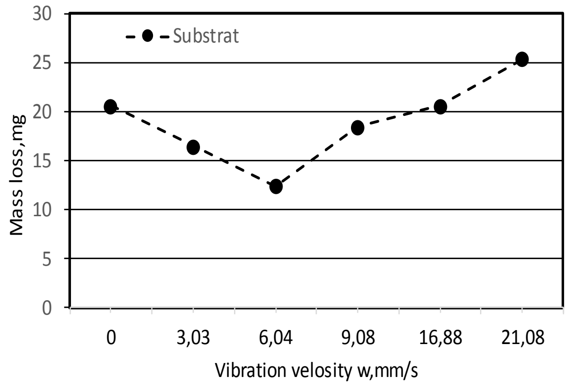


Figure 8. Mass loss variation with the vibration speed for the substrate.

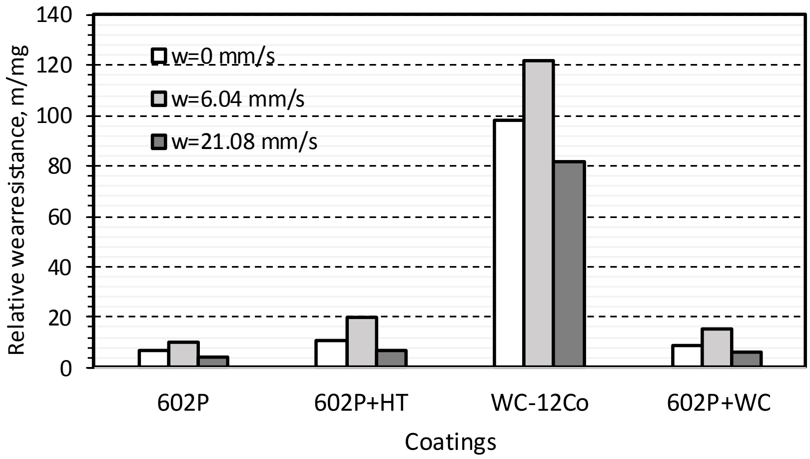


Figure 9. Diagram of the relative wear resistance of coatings with and without vibration.

Figure 9 shows the diagram of the relative wear resistance of the coatings for the cases without vibration and for two values of the vibration speed.

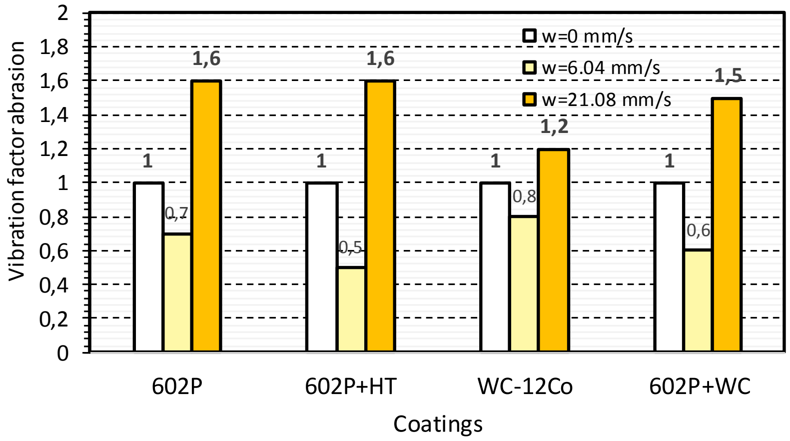


Figure 10. Diagram of the vibration factor at abrasion for all coatings.

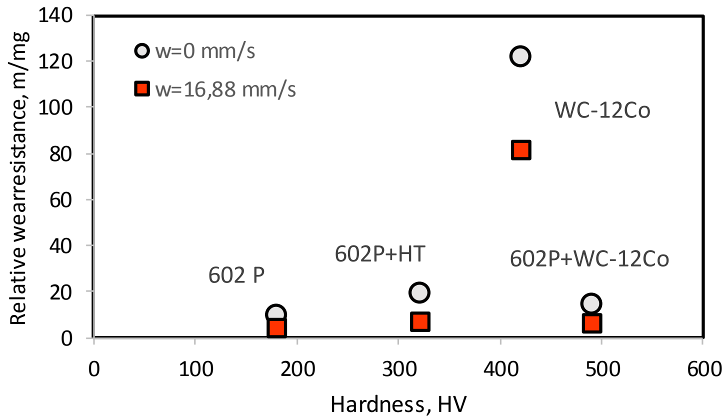


Figure 11. Variation of the relative wear resistance with coatings hardness before friction and after friction without and with vibration.

Figure 10 shows the diagram of the vibration factor during abrasion for all coatings, and figure 11 shows the relationship between the relative wear resistance and the hardness of the coatings before friction, after friction without and with vibration and the hardness of the coatings measured before friction.

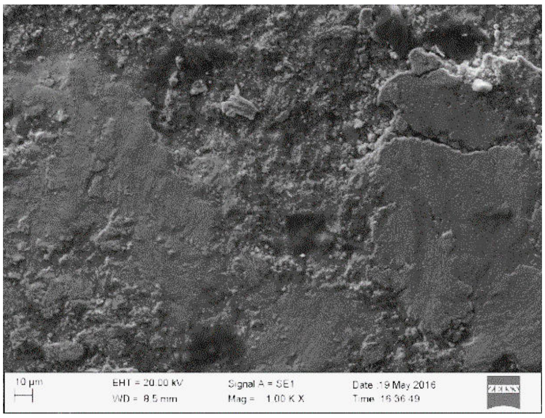


Figure 12. Morphology of 602P coating on steel.

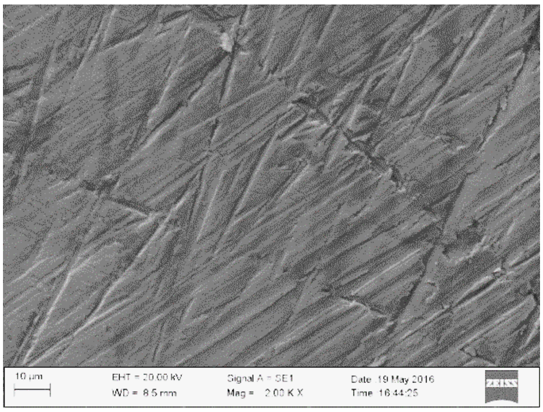


Figure 13. Morphology of 602P+HT 650°C coating on steel

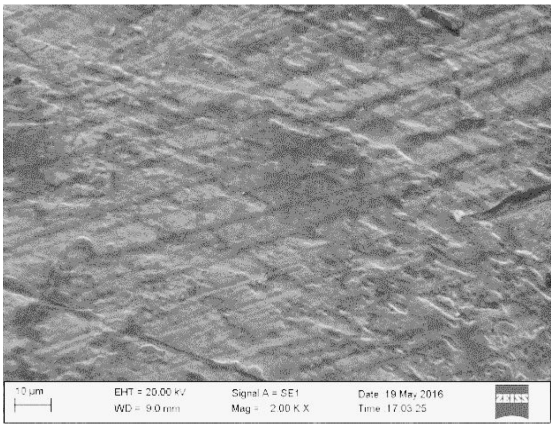


Figure 14. Morphology of WC-12Co coating on steel.

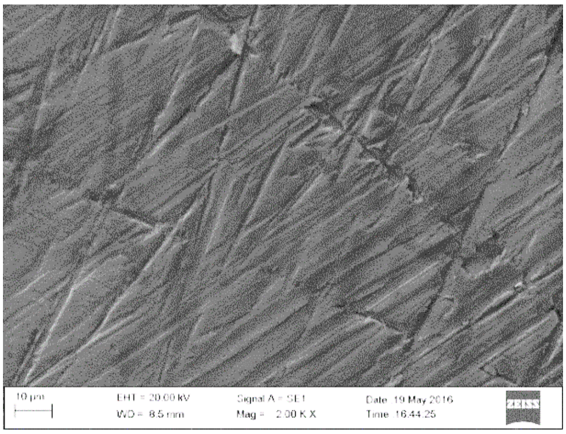


Figure 15. Morphology of 602P+WC-12Co coating on steel.

Figures 12 - 15 give the morphology of the coatings after abrasive friction at vibration speed of 21.08 mm/s.

4. Discussion and conclusions

The basic interpretations and conclusions of the present study are as follows:

- The value of the vibration speed influences the value and the character of variation of coatings mass wear. The wear decreases up to a given vibration speed value, then increases and for w > 16,88 mm/s the amount of wear attains higher values than those without vibration (figures 5,6,7);
- The relationship between wear and vibration speed shows nonlinear character with a minimum value, which appears for all specimens at vibration speed 6.04 mm/s (figures 5,6,7,8);
- Lowest wear for all specimens in the whole interval of vibration speed shows the coating WC-12Co, the wear of which is a whole order of magnitude lower than those of the other coatings. The relation between wear and vibration speed also shows a minimum at w = 6.04 mm/s, however at higher speeds w > 16.88 mm/s the wear exhibits a constant value close to the value under conditions without vibration (figure 6);
- The preliminary heating of the substrate to 650°C during 5 min at the deposition of 602P coating results in decrease of wear with 55% for the entire interval of vibration speed variation (figure 5). With the change of the vibration speed, the relative wear resistance varies less compared with the other coatings, its value being close to that for the case without vibration (figures 9,10);
- The wear and the relative wear resistance of the combined coating 602P+WC-12Co(1:1) are not much different from those of coatings 602P and 602P+HT650°C (figures 9,10);
- Highest hardness shows the coating 602P+WC-12Co (1:1) before friction, and after friction without and with vibration speed 21.08 mm/s (table 7). This coating however does not exhibit the highest relative wear resistance (figure11). This fact confirms the idea that for composite coatings and materials there is not always a correlation between the hardness and the wear resistance;
- The analysis of the morphology of the coatings after abrasive wear at vibration speed 21.08 mm/s shows that in the case of the coating WC-12Co the basic wear mechanism is mechanical scratch by the abrasive particles during the relative motion. Figure 14 shows that the worn coating has a homogeneous texture in the shape of plane network of scratches obtained by the plane motion of the specimen. The high wear resistance of the coating is related to the specific individual functions of the components in its structure: the WC particles assure high resistance of the coating against the cutting tangential action of the abrasive particles and the fatigue strength to vibrations of the coating; the cobalt (Co) plays the contact role in coating structure building internal boundary network between the WC particles and guaranties the wholeness of the coating. The wear resistance of composite coatings is mostly determined by the thickness and the physical and mechanicals properties of this network. The internal contact network defines in many cases the damping properties of the coating under conditions of pulse and periodical perturbations;

- The basic mechanism of wear for coatings 602P and 602P+WC-12Co (1:1) is fatigue destruction of the surface due to the periodically varying load with high vibration speed (figures 12 and 15).

The overall conclusion is that the operation of machinery and equipment under extreme conditions of vibration load and abrasive friction is optimal in the case of WC-12Co coatings deposited through HVOF technology. The preliminary heating of the substrate during 602P coating deposition leads to 50% wear resistance improvement.

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