

**TRIBOLOGICAL STUDIES
OF HIGH VELOCITY OXY-FUEL (HVOF)
SUPERALLOY COATINGS**

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ABSTRACT

High technology coatings layers on super alloys hardfaced by HVOF technology have very high wear resistance under extreme working conditions – adhesion, abrasion, corrosion cavitation and vibrations. In the present work investigations have been carried out on wear of coating layers formed by HVOF under the conditions of dry friction on abrasive surface. The total number of studied samples is 12 powder compositions coated on nickel matrix (502P, 602P, 80M60) and tungsten matrix (6P50W, SX199, WC-12Co) at one and the same temperature of hardfacing. From each of the powders are obtained coatings without preliminary heating and with preliminary heating of the substrate in a chamber at 650°C. New and interesting results are presented on the wear characteristics and the loads plus the friction path. The influence of the preliminary heating on the wear rate and the relative wear resistance is tested and also the connection between abrasive wear and the hardface of the coatings.

Key words: HVOF coatings, tribology, wearing off

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AIMS AND BACKGROUND

The wearing off process is a fundamental problem, connected with the working capacity, the resource and reliability of the mechanisms and machines. It leads to losses of material and human resources and it is the reason for decommissioning from exploitation of more than 90% of the details and machines.

It has been established that the utilization of the achievements of the contemporary tribology science enables reducing many times the losses originating from friction and wearing off processes in machines, which would lead to an economical effect of about 2% up to 4% of the national income of the developed countries in the world. The integrity of the technical-economical and ecological aspects of tribology is due to the circumstance that the character of the tribological processes, besides limiting the working capacity and reliability of the machines, leads also to pollution of the environment by heat or acoustic emissions, solid, liquid or gaseous toxic emissions.

At present there are three main approaches, which are outlined in the tribology, solving the problems, caused by the friction and resulting in wearing off. The most widely occurring approach to reduce the degree of wearing off in tribological systems is connected with the development of new kinds of materials, coatings and technologies for enhancing the hardness of the contact surface. Upon increasing the hardness of the surface layers the degree of mutual penetration of roughnesses on the surface of the body on the surface of the counterbody is decreased, whereupon the plastic deformations are decreased, as well as the oxidation processes and the action of abrasive particles, products from the wearing off process. This statement is based on the assumption, that the high wear resistance and respectively the resource of the machine details is in direct dependence on the hardness of the surface layers.

Numerous methods and technologies have been elaborated for enhancing the hardness of the surface layers and the coatings. On the basis of this approach many technical problems have been solved, associated with the promoting of the resource and reliability of contact conjunctions in machines¹⁻⁸.

One of the methods for promoting the exploitation resource of equipment, operating under extreme exploitation conditions – abrasion, erosion, corrosion, impact and vibration high loading is connected with the enhancement of the wear-resistance of the surface by depositing some coatings applying the HighVelocity Oxy-Fuel (HVOF) technology⁷⁻²⁵. HVOF is a contemporary tribotechnology method for obtaining of highly wear-resistant coatings, which are used for machine details, contact conjunctions and surfaces for equipment in the field of different kinds of transportation, the mining industry, energy production, gas extraction and petroleum industry, road processing machines etc. The essence of the HVOF technology for preparing coatings consists in impact contact interaction between

powder particles, moving at supersonic speed in a flame jet, and the surface of the material (substrate), upon which the coating is being deposited¹⁰⁻¹⁷.

The fuel (kerosene, acetylene, propylene and hydrogen) and the oxygen are being fed into the fuel chamber, from which the burning flame is released having temperature $> 3000\text{ }^{\circ}\text{C}$ and it is flowing out at high pressure through a nozzle at supersonic speed. The powder composition is being fed axially into the fuel chamber under high pressure or into the nozzle in the direction, where the pressure is lower (Fig. 1).

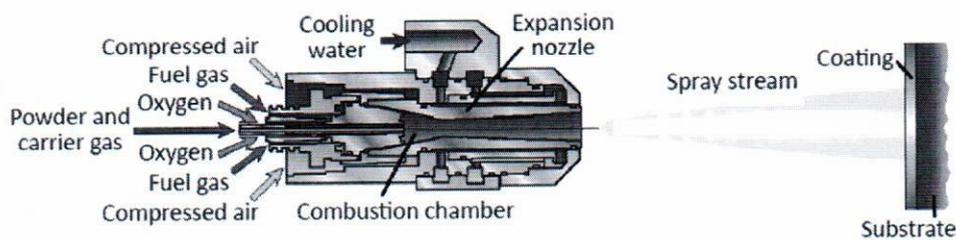


Fig. 1. Schematic drawing of the high velocity oxygen-fuel spraying (HVOF) process with gas-fuel gun² (Reproduced by permission of Oerlikon Metco)

The powder compositions, known in the specialized literature as *powder super alloys*, represent compositions of particles of different metals, alloys, ceramics, and polymer materials having micron sizes. The particles, carried away by the flame stream, are passing over into plastic or semi-plastic state in the form of particle or droplet and after contact with the substrate they are deformed and take the shape of thin lamellas. Upon striking the roughnesses the particles-droplets are being cooled down forming adhesion and cohesion contact bondings with the basal surface and between themselves forming laminar structure of the composite coating¹³⁻²¹.

The object of the present work was to carry out a comparative investigation of composite coatings of various super-alloys, deposited by means of HVOF technology, under the conditions of dry friction over surface with fixed abrasive under the effect of different normal loading.

MATERIALS AND DEPOSITION CONDITIONS

11 types of coatings have been studied, deposited by the HVOF technology method using metal, metallic-ceramics and ceramic powder compositions based on nickel – 602P, 80M60; based on tungsten – 6P50W, WC-12Co, dichromium trioxide - Cr_2O_3 and combination of the three compositions based on nickel and tungsten at a

ratio 1:1:1- 602P-6P50W- (WC-12Co). The average size of the powder particles is about $45 \pm 2,5 \mu\text{m}$, obtained as a result of agglomeration process including a stage of sintering.

The selection of powder compositions has been made assuming that the exploitation resource should be increased to the maximum – both that of the contact surfaces as well as that of the conjunctions by promoting their wear resistance under the conditions of abrasive wearing off process, applied in various fields of the Bulgarian industry.

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 $193.6 \div 219.5 \text{ HV}$.

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	0.20	0.55	0.30	0.45	0.045	0.30	Balance

The preliminary treatment 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 on 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 vapor-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 granulometric composition of the abrasive in mm as percent ratio as follows: $3.15 \div 1.4 \text{ mm} - 9.32\%$; $1.63 \div 0.5 \text{ mm} - 16.4\%$; $1.4 \div 1.0 \text{ mm} - 15.8\%$; $1.0 \div 0.63 \text{ mm} - 39.6\%$; $0.5 \div 0.315 \text{ mm} - 9.32\%$; $0.315 \div 0.16 \text{ mm} - 9.32\%$; particles of size below 0.15 mm different fractions – up to 100% of the following chemical compounds: $\text{SiO}_2 - 41\%$, combined in the form of silicates; $\text{Al}_2\text{O}_3 - 8.3\%$, $\text{MgO} - 6.6\%$, $\text{CaO} - 5.5\%$ and $\text{MnO} - 0.4\%$. The technical parameters of the mobile system for blasting are: input pressure 8 atm; operating pressure in the nozzle – 4 atm; diameter of the nozzle $\phi - 7 \text{ mm}$; distance between the nozzle and the surface – 30 mm; angle of interaction of the stream with the surface – 90° . The coatings, deposited with the compositions 602P, 80M60, 6P50W and the combined three compositions 1:1:1 – 602P-6P50W- (WC-12Co) are studied in two experimental runs: without any preliminary thermal treatment of the substrate and after preliminary thermal treatment. The thermal treatment consists in heating of the substrate up to a temperature of 650°C in a chamber with duration of 5 minutes, and then the coating is deposited. Coatings deposited on thermally treated substrate are denoted by PHS*. One of

the coatings (80M60) is deposited on substrate of aluminium alloy (Al-Cu) after preliminary thermal treatment.

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

Table 2. Technological regime parameters for HVOF coating deposition

No	Parameter	Technological regime
1.	Propylene/oxygen ratio, %	55/100
2.	Jet velocity, m/s	1000
3.	Distance „nozzle-coating” L, mm	100
4.	Angle between nozzle and coating, α , grad	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 notations (designations) and the chemical composition (wt. %) of the studied coatings are represented in Table 3.

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

Sample	Coating designation	Powder chemical composition, wt. %
1	602P, Substrate: Steel	Cr: 13.2; Si: 3.98; B: 2.79; Fe: 4.6; Co: 0.03; C: 0.63; Ni: Balance
2	602P: PHS*, Substrate: Steel	
3	80M60, Substrate: Steel	Cr: 14.2; Si: 4.37; C: 0.6; B: 2.9; Fe: 4.54; Cu: 2.36; Mo: 2.51; Co: 0.01; Ni: Balance
4	80M60: PHS*, Substrate: Steel	
5	80M60: PHS*, Substrate: Al	
6	6P50W, Substrate: Steel	Cr: 13.15; Si: 4.28; B: 2.87; Fe: 0.04; Ni: 29.6; Co: 0.04; C: 0.58; W: Balance
7	6P50W: PHS*, Substrate: Steel	
8	WC-12Co, Substrate: Steel	Co: 12; C: 5.4; Fe: < 0.1; Ni: < 0.1; W: Balance
9	602P-6P50W-(WC-12Co) Substrate: Steel	Mixture ratio (1:1:1)
10	602P-6P50W-(WC-12Co): PHS* Substrate: Steel	
11	Cr ₂ O ₃ , Substrate: Steel	Al ₂ O ₃ < 0.03; SiO ₂ < 0.07; Fe ₂ O ₃ < 0.02; CaO < 0.03; MgO < 0.01; TiO ₂ < 0.02; Cr₂O₃: Balance

MICROSTRUCTURE, THICKNESS, ROUGHNESS AND HARDNESS CHARACTERISTICS OF TESTED COATINGS

Table 4 represents data on the thickness, porosity, hardness and roughness of the coatings without any mechanical treatment.

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

Sample	Coating designation	Thickness μm	Porosity %	Roughness μm	Hardness HRC
1	602P Substrate: Steel	120	1.5	Ra=2.888	62
2	602P: PHS* Substrate: Steel	120	1.4	Ra=0.168	63
3	80M60 Substrate: Steel	115	3	Ra=5.798	63
4	80M60: PHS* Substrate: Steel	115	1.8	Ra=2.148	60
5	80M60: PHS* Substrate: Al	120	2.0	Ra=6.659	62
6	6P50W Substrate: Steel	110	1.6	Ra=6.832	65
7	6P50W: PHS* Substrate: Steel	115	1.4	Ra=3.832	68
8	WC-12Co Substrate: Steel	120	1.3	Ra=5.484	70
9	602P-6P50W-(WC-12Co) Substrate: Steel	120	1.5	Ra=3.028	68
10	602P-6P50W-(WC-12Co): PHS* Substrate: Steel	115	1.4	Ra=5.996	70
11	Cr ₂ O ₃ Substrate: Steel	110	3	Ra=3.332	59
12	Substrate: Steel	-	-	Ra=0.57	-
13	Substrate: Al	-	-	Ra=0.488	-

The roughness (Ra, Rq) of the coatings has been measured using profile-meter TESA Rugosurf 10-10G in two perpendicular directions. The thickness of the coatings has been measured by Pocket Leptoskop 2021 Fe. The measurements have been carried out in 10 points on the surface and the following mean arithmetic value has been calculated. The measurement of the hardness of the coatings has been done using hardness-meter by Rockwell (HRC). The hardness has been determined as mean arithmetic value of three measurements for each one of the samples in order to eliminate some possible effects of segregation and in order to obtain more realistic impression about it.

The microstructure of the samples of the studied coatings has been revealed by using cross-sections and applying optical microscope. Figure 2 represents the microstructure of some of the studied coatings.

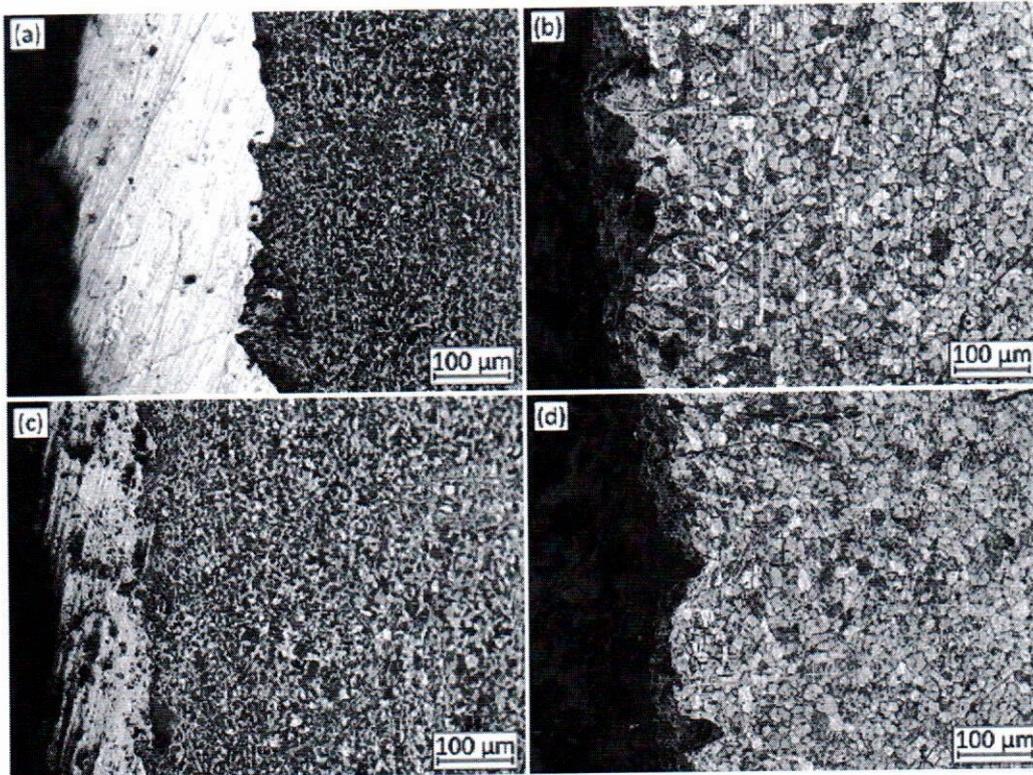


Fig. 2. Microstructure properties of some of the tested coatings: (a) Coating 602P, (b) Coating 80M60: PHS, (c) Coating WC-12Co, (d) Coating 6P50W-602P-(WC-12Co)

ABRASIVE WEAR: EXPERIMENTAL DETAILS

The abrasive wear of the coatings has been studied during dry friction of the surface with fixed solid abrasive particles. The study has been carried out using a tribo-tester of the type „Pin-on-disk”. The functional scheme of the tribo-tester is represented in Figure 3.

The studied sample with a coating (1) is attached and fixed firmly in the bed of the holder (2), placed in the loading head (8). The forehead surface of the sample (1) is in contact with the surface of the counterbody (3), fixed firmly on a horizontal disk (4). The disk (4) is being driven by electromotor (6) and it is rotating around its vertical central axis at a constant angular rate ω .

The normal loading P is applied in the center of gravity of the contact area between the sample and the surface and it is being driven by the lever system in the loading head (8). The friction path length is set by the number of cycles measured by rotameter 7.

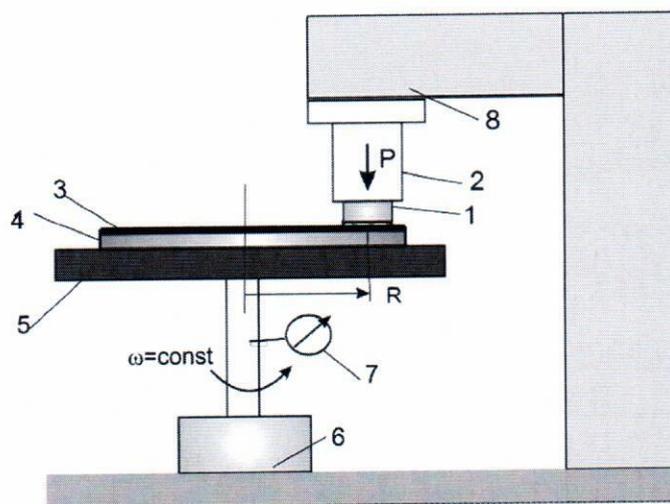


Fig. 3. Schematic diagram of abrasive wear testing on pin-on-disc tribometer

The device enables changing of the sliding velocity varying within the limits from 0,55 m/s up to 1 m/s by varying the distance R between the axis of rotation of the disk (4) and the axis of the sample (1).

The samples represent square-form plates of dimensions $15 \times 15 \times 6.0$ mm.

The study has been carried out under the following conditions: nominal contact area – $A_a = 2.25 \times 10^{-6}$ m²; sliding velocity – $V = 0.155$ m/s; friction path length – $L = 24.5$ m; type of the abrasive surface – Corundum P 320; normal loading – $P = 2.5$ N; 5N; 7.5N; 10N.

The methodology of investigation of the characteristics of the wearing off process consists in measuring of the mass amount worn off the samples at a definite friction path length (time interval of friction) under fixed set of conditions – loading and sliding velocity. The methodology comprises the following sequence of operations:

- Preliminary preparation of the samples having identical size and measurement of the roughness, thickness and hardness of the coatings;
- Measurement of the mass m_0 of the sample prior to the friction by means of electronic balance WPS 180/C/2 with a precision of 0.1 mg. Before each measurement with the balance the sample is purified from mechanical and organic particles, dried up with ethyl alcohol in order to prevent possible electrostatic effect;
- The sample is placed in the holder of the loading head, a certain normal loading value P is set and the number of cycles of friction (friction path length);
- The mass of the sample m_1 is measured and the following characteristics of the wearing off process are calculated:

Worn off mass m :

$$m = m_o - m_i, \text{ mg} \quad (1)$$

Specific wear i_r – the mass destroyed during the friction of the surface layer at normal loading $P=1\text{N}$ per unit of length of friction path $L=1\text{ m}$:

$$i_r = \frac{m}{PL}, \text{ mg/Nm} \quad (2)$$

Relative wear ε_r – the ratio between the specific wear of the substrate i_{sb} and the specific wear of the studied sample:

$$\varepsilon_r = \frac{i_{sb}}{i_r} \quad (3)$$

The relative wear parameter ε_r is a non-dimensional quantity, which shows how many times the wearing off degree of the tested sample is smaller than the wearing off degree of the substrate under identical conditions of friction.

The influence of the preliminary thermal treatment of the substrate upon the degree of wearing off is evaluated based on the factor ε_{ij} , which is calculated as the ratio between the specific wear after thermal treatment and the specific wear without any heating of the substrate:

$$\varepsilon_{ij} = \frac{i_r^{PHS}}{i_r} \quad (4)$$

All the above described operations are repeated for each loading value P .

RESULTS AND DISCUSSION

Table 5 represents the experimental results on the mass wearing, while Table 6 – the data on the specific wear for the tested coatings at four different values of the loading.

Table 5. Abrasive wear of tested coatings

Sample	Coating designation	Load, N			
		2.5	5	7.5	10
		Mass loss, mg			
1	602P Substrate: Steel	0.8	1.3	0.6	2.7
2	602P: PHS* Substrate: Steel	0.6	0.9	0.4	2.0
3	80M60 Substrate: Steel	2.0	3.1	4.9	7.1
4	80M60: PHS* Substrate: Steel	0.9	1.2	2.5	3.4
5	80M60: PHS* Substrate: Al	3.9	4.1	5.1	5.7
6	6P50W Substrate: Steel	0.5	1.0	1.4	1.6
7	6P50W: PHS* Substrate: Steel	0.4	0.6	0.8	0.9
8	WC-12Co Substrate: Steel	0.3	0.5	0.8	0.9
9	602P-6P50W-(WC-12Co) Substrate: Steel	1.0	1.2	1.1	1.1
10	602P-6P50W-(WC-12Co): PHS* Substrate: Steel	1.2	1.7	1.1	0.6
11	Cr ₃ O ₃ Substrate: Steel	13.4	16.7	18.5	20.4
12	Substrate: Steel	6.4	3.7	6.6	14.1
13	Substrate: Al	5.8	12.7	19.5	26.2

Table 6. Specific wear of tested coatings

Sample	Coating designation	Load, N			
		2.5	5	7.5	10
		Specific wear, mg/Nm			
1	602P Substrate: Steel	1.3×10^{-2}	1.1×10^{-2}	1.0×10^{-2}	1.1×10^{-2}
2	602P: PHS* Substrate: Steel	0.9×10^{-2}	0.7×10^{-2}	0.8×10^{-2}	0.8×10^{-2}
3	80M60 Substrate: Steel	3.3×10^{-2}	2.5×10^{-2}	2.7×10^{-2}	2.8×10^{-2}
4	80M60: PHS* Substrate: Steel	1.5×10^{-2}	1.0×10^{-2}	1.4×10^{-2}	1.4×10^{-2}
5	80M60: PHS* Substrate: Al	6.4×10^{-2}	3.3×10^{-2}	2.8×10^{-2}	2.3×10^{-2}
6	6P50W Substrate: Steel	0.8×10^{-2}	0.8×10^{-2}	0.8×10^{-2}	0.7×10^{-2}
7	6P50W: PHS* Substrate: Steel	0.7×10^{-2}	0.5×10^{-2}	0.4×10^{-2}	0.4×10^{-2}
8	WC-12Co Substrate: Steel	0.5×10^{-2}	0.4×10^{-2}	0.4×10^{-2}	0.4×10^{-2}
9	602P-6P50W-(WC-12Co) Substrate: Steel	1.6×10^{-2}	1.0×10^{-2}	0.6×10^{-2}	0.5×10^{-2}
10	602P-6P50W-(WC-12Co): PHS* Substrate: Steel	2.0×10^{-2}	1.0×10^{-2}	0.6×10^{-2}	0.2×10^{-2}
11	Cr ₃ O ₃ Substrate: Steel	21.9×10^{-2}	13.6×10^{-2}	10.1×10^{-2}	8.3×10^{-2}
12	Substrate: Steel	10.4×10^{-2}	3.0×10^{-2}	3.6×10^{-2}	5.8×10^{-2}
13	Substrate: Al	9.5×10^{-2}	10.4×10^{-2}	10.6×10^{-2}	10.7×10^{-2}

The Table 7 and Table 8 list the results respectively for the relative wear ε and for the factor ε_{ij} for the tested coatings.

Table 7. Relative wear of tested coatings

Sample	Coating designation	Load, N			
		2.5	5	7.5	10
		$\varepsilon_{ij} = i_{sb}/i_r$			
1	602P Substrate: Steel	8.0	2.7	12	5.3
2	602P: PHS* Substrate: Steel	11.6	4.3	15	7.3
3	80M60 Substrate: Steel	3.2	1.2	1.3	2.1
4	80M60: PHS* Substrate: Steel	6.9	3.1	2.6	4.2
5	80M60: PHS* Substrate: Al	1.5	3.2	3.8	4.7
6	6P50W Substrate: Steel	13.0	3.8	4.7	8.9
7	6P50W: PHS* Substrate: Steel	16.0	6.1	8.2	15.7
8	WC-12Co Substrate: Steel	21.0	7.3	8.2	15.7
9	602P-6P50W-(WC-12Co) Substrate: Steel	6.5	3.1	6.0	12.9
10	602P-6P50W-(WC-12Co): PHS* Substrate: Steel	5.3	2.2	6.0	24.0
11	Cr ₂ O ₃ Substrate: Steel	0.5	0.2	0.3	0.7
12	Substrate: Steel	1	1	1	1
13	Substrate: Al	1	1	1	1

Table 8. Influence of the thermal treatment of the substrate on the specific wear

Sample	Coating designation	Load, N			
		2.5	5	7.5	10
		$\varepsilon_{ij} = i_r^{PHS}/i_r$			
1	602P Substrate: Steel	1.5	1.6	1.3	1.4
2	602P: PHS* Substrate: Steel				
3	80M60 Substrate: Steel	2.2	2.6	2.0	2.0
4	80M60: PHS* Substrate: Steel				
5	80M60: PHS* Substrate: Al	-	-	-	--
6	6P50W Substrate: Steel	1.2	1.6	1.7	1.8
7	6P50W: PHS* Substrate: Steel				
8	WC-12Co Substrate: Steel	-	-	-	-
9	602P-6P50W-(WC-12Co) Substrate: Steel	0.8	0.7	1.0	1.9
10	602P-6P50W-(WC-12Co): PHS* Substrate: Steel				
11	Cr ₂ O ₃ Substrate: Steel	-	-	-	-

The Figures 4, 5, 6, 7 and 8 represent graphically the dependence of the mass wearing off as a function of the normal loading for all the tested coatings. The Figures 9, 10 and 11 illustrate the diagrams of the specific wear of the coatings.

On the basis of the analysis of the obtained results on the abrasive wear of the composite coatings, deposited by the HVOF technology method, the following statement can be formulated:

Upon increasing the normal loading the degree of wearing off is increasing, but the dependence has a different character for the separate coatings. For coatings with nickel and tungsten matrix, deposited on substrate of steel one can observe straight proportional dependence up to loading values $P=7.5\text{N}$. At higher loadings

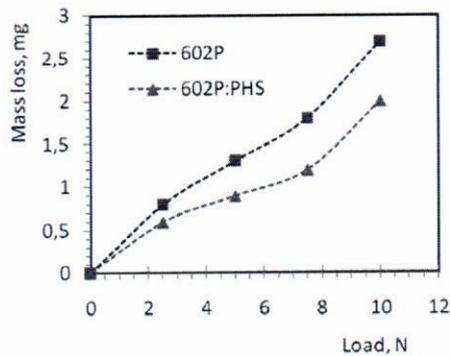


Fig. 4. Mass loss vs. load for coatings 602P and 602P: PHS*

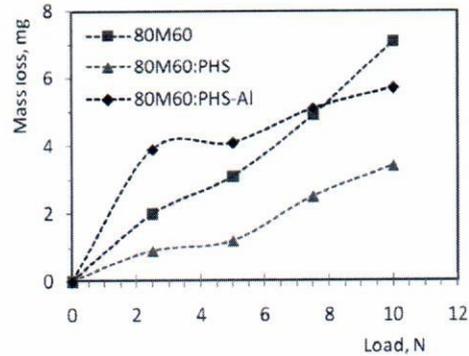


Fig. 5. Mass loss vs. load for coatings 80M60 (sub.Steel) and 80M60(sub. Steel): PHS* and 80M60 (su. Al): PHS*

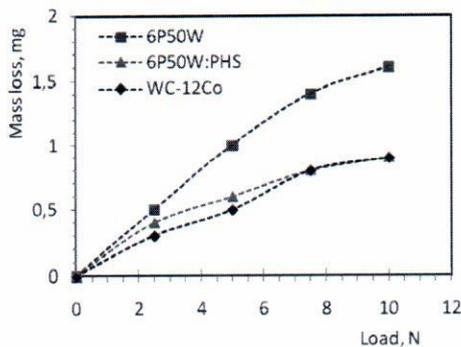


Fig. 6. Mass loss vs. load for coatings 6P50W and 6P50W: PHS* and WC-12Co

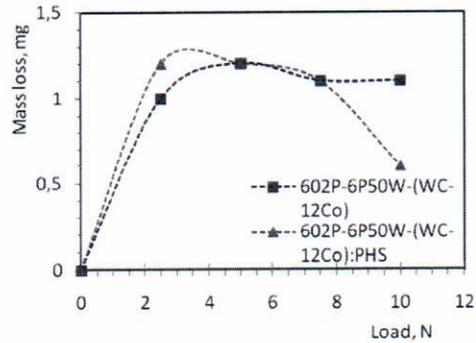


Fig. 7. Mass loss vs. load for coatings 602P-6P50W-WC-12Co and 602P-6P50W-(WC-12Co): PHS*

$P > 7.5\text{N}$ the dependence of wear on the normal loading has non-linear character, while for coatings with nickel matrix the wearing rate is sharply increasing (Figures 4 and 5) and for coatings with tungsten matrix the wearing degree is growing up at a very low rate (Figure 6).

In the cases of coatings, deposited from three powder compositions: 602P-6P50W- (WC-12Co) a very interesting result is observed (Figure 7). In the case without any preliminary thermal treatment of the substrate at low loading value $P = 2.5\text{N}$ the wearing degree increases, while at loading $P > 2.5\text{N}$ it decreases and remains constant at $P = 5.5 \div 10\text{N}$.

The wear of samples of substrate of steel and aluminum and coating of Cr_2O_3 is much bigger than the wearing degree of the rest of the coatings (Figure 8). The dependence of the wearing degree of a sample of aluminum has linear character and at loading $P > 7.5\text{N}$ the greatest wear of the three samples is observed. The lowest wear degree is that of the steel sample, which remains constant within the range up to $P = 7.5\text{N}$. At loading $P = 10\text{N}$ the wearing off degree sharply grows up, but it still remains lower than the wear of the coating of Cr_2O_3 and that of the sample of Al.

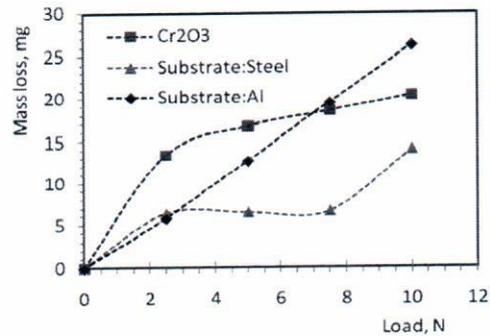


Fig. 8. Mass loss vs. load for coatings Cr_2O_3 , substrate steel and substrate Al

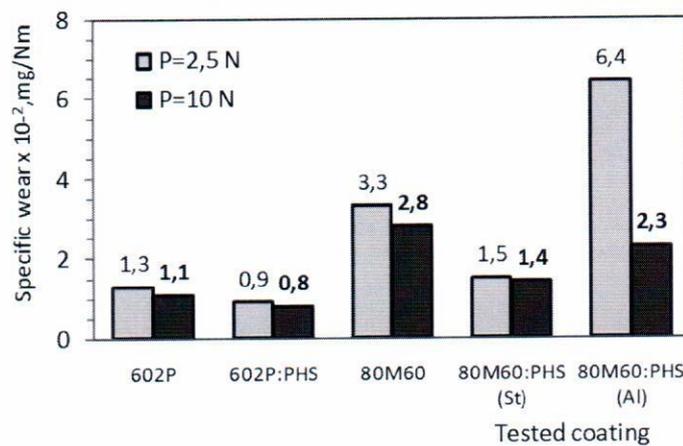


Fig. 9. Comparative specific wear values for coatings 602P, 602P:PHS*, 80M60 (Steel), 80M60(sub.Steel):PHS*, 80M60(sub.Al):PHS*

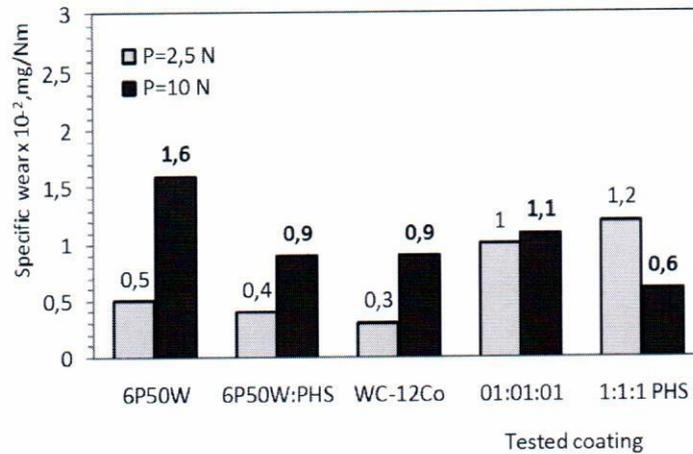


Fig. 10. Comparative specific wear values for coatings 6P50W, 6P50W :PHS*, C-12Co, 1:1:1, 1:1:1:PHS*

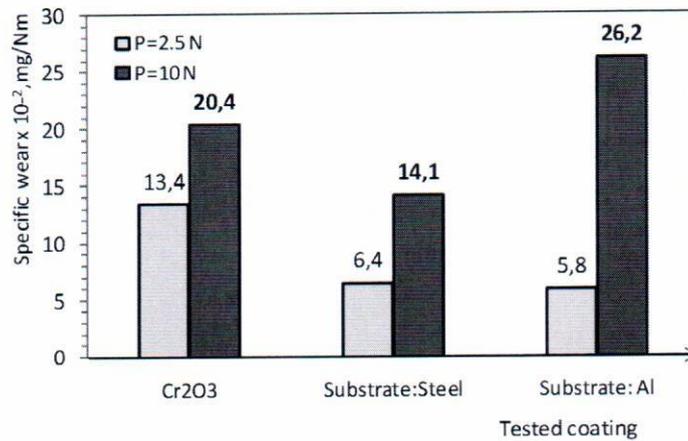


Fig. 11. Comparative specific wear values for coating Cr₂O₃ and substrate steel and substrate Al

Among all the studied samples with and without preliminary thermal treatment of the substrate the lowest wear degree is shown by the sample having coating of WC-12Co at all values of the normal loading (Figure 6). Close values of wearing degree is shown by the coating based on tungsten 6P50W: PHS having thermal treatment of the substrate. The high abrasive wear-resistance of the coating WC-12Co is not surprising. It is due to the combination of very hard carbides and

the hard, but with certain plasticity matrix of cobalt Co. The good wetting of the tungsten carbides in the cobalt matrix contributes to the high cohesion strength of the metal-ceramics WC-Co. In other words, inside the bulk phase of the coating an internal contact network is being formed, having high mechanical strength characteristics, which ensure high resistance of the coating against destruction as a result of the scratching action of the abrasive particles. The systematic studies of other authors on WC-Co coatings with different percentage of the cobalt content – 12, 17 and 25% show that the lowest wear is demonstrated by coatings WC-12Co, i.e. containing 12% cobalt.

A prerequisite for the high abrasive wear-resistance of coatings WC-12Co, deposited by the HVOF technology, is their low porosity – 1,3%, which is the lowest value of the porosity for all studied coatings. The low porosity, i.e. the high compactness of the coating is connected with the liberation of particles and gases from the substrate in the process of depositing the coating. The liberation of carbon can be induced on one side in case of its oxidation into carbon monoxide ($2C + O_2 \rightarrow 2CO$), while on the other side it is the result from diffusion processes.

In comparison with the other thermal spray technologies the HVOF technology is one of the best methods for the preparation of metal-ceramic WC-Co coatings. The short time interval of residence of the particles inside the flame in the case of this technology with super-sonic speed and the relatively low temperatures lead to smaller degree of destruction of the compound WC. This fact gives us the reason to accept that the decomposition of the compound WC in the process of deposition of the coating is reduced to a minimum, which ensures its high abrasive wear resistance.

The preliminary thermal treatment of the substrate leads to decrease in the specific wear for all studied coatings (Table 8), but to a different extent. The strongest influence of the thermal treatment is observed with the coating 80M60, but this influence depends on the magnitude of the normal loading. Under loading $P=2.5N$ up to $P=5N$ the extent of this influence is greatest and the specific wear drops down to 2.2 up to 2.6 times. Under loading $P=7.5N$ up to $P=10N$ the specific wear is decreased 2 times. For coatings, deposited with three powder depositions under loading up to 7.5 N the preliminary thermal treatment has no positive effect – the specific wear is increasing. Under high loading, however, the specific wear decreases down to 2 times.

CONCLUSIONS

In the present paper comparative studies are carried out on 11 types of coatings made with the High Velocity Oxy-Fuel (HVOF) technology under the conditions of dry friction of the surface with attached abrasive particles.

The obtained results concern the effect of the normal load, additional heat processing of the substrate and the type of the underlying layer, on the characteristics of the abrasive wear.

It has been found out that the abrasive wear depends on the value of the normal load and it has a different character in the cases of different coatings. At small values of the load this dependence is proportional and at higher values of the load the dependence is no longer linear.

The value of wear depends on the preliminary heat processing of the substrate. For coating on a steel surface the wear is smaller than for the wear of coatings on aluminium surface. A preliminary heating of the substrate leads to the decrease of all coatings tested, but to a different extent.

The greatest wear of all the tested samples shows the WC-12Co coating on steel. The latter is a combination of very hard carbides and plastic matrix of cobalt. The high abrasive wear resistance is due to the high degree of wetting of the tungsten carbides in the cobalt matrix and as a result in the coating is built up an internal contact net with high cohesion technological toughness of the metaloceramics WC-Co. The homogeneity of this net is of exclusive importance for the high mechanical and tribological characteristics of the WC-12Co coating. The initial heat processing of the steel seat leads to an abrasive wear resistance of the coating 6P50W: PHS. The latter one has as next to the best wear resistance in our study.

The biggest abrasive wear in all tested samples shows the coating of Cr_2O_3 , which is greater than the wear of steel and aluminum substrate under a normal load of 7.5 N. Under high load $e = 10\text{N}$, the wear has the values of which is in-between both substrates. This results shows that the coating of Cr_2O_3 , made by HVOF technology is not suitable for surfaces and details working in the abrasion conditions.

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