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WEAR OF GAS-FLAME COMPOSITE COATINGS WITH TUNGSTEN AND NICKEL MATRIX. PART I. ABRASIVE WEAR

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Abstract. The object of the study is the characteristics of wear and wear-resistance of composite powder coatings, deposited by means of supersonic flame stream (or high velocity oxygen fuel spraying HVOF). Two types of coatings have been obtained – a group of powder composites based on tungsten matrix and a second group based on nickel matrix, whereupon each group includes coatings having different sizes of the powder particles. The coatings have been tested in two cases – in case of abrasion and in case of erosion. The present work consists of two parts. The first part represents the results on the characteristic features of wearing off during dry friction on the surface with fixed abrasive particles. Results have been obtained about the dependences of mass wear, the rate of wearing off, the wear intensity, absolute and relative wear-resistance under the same conditions of friction. It has been established that the coatings of powder composites based on tungsten matrix (coating SX199/11) having size of the particles 11 μm possess the highest wear-resistance among all the tested coatings. The increase in the size of the particles 4 times leads to decrease in the wear resistance with an order of magnitude. In the case of nickel matrix coatings one observes the same effect – at small size – 20 μm (coating 1660-22/20) the wear resistance is almost three times higher than that of coating having the same composition, prepared of particles of size 45 μm (coating 1660-22/45).

Keywords: High Velocity Oxygen-Fuel (HVOF) coatings, tribology, abrasion wear, erosion wear.

AIMS AND BACKRGOUND

The green tribology is a new interdisciplinary scientific research direction within the functional space of the tribology, directed to stable development of the society

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in its coexistence with the nature and the environment. The green tribology gained popularity among the thousands of tribologists around the world and it became a substantial part of the organisational activity of the International Council on Tribology since the beginning of the 21st century. Some researchers define the term 'green tribology' as 'the science and technology of tribology aspects of the ecological equilibrium'[1–4].

The central purpose of the green tribology is focused on the improvement of the quality of life of mankind by means of optimisation of its contact interaction with the nature[1].

The most often applied approach in tribology for reducing the wearing off degree in the tribo-systems is connected with the elaboration of new technologies, materials and coatings for promoting their exploitation and ecological characteristics[5–10]. Such technology appears to be the method for the deposition of highly wear resistant composite coatings with supersonic flame stream, known as High Velocity Oxygen-Fuel (HVOF) spraying[6–12].

The characteristic features of the coatings to a great extent depend on the sizes, their nature and on the temperature of the superficial layer of the particles and the substrate[13–21].

The aims of the present research work are the characteristics of wearing off and the wear resistance of composite powder HVOF-coatings, with tungsten and nickel matrix, whereupon each group includes coatings with different micron sizes of the powder particles. All the coatings have been tested in two cases of friction – during abrasion on the surface with attached abrasive and erosion from air stream, carrying solid abrasive particles. The results are represented in two separate parts: the first part is devoted to the characteristics of abrasive wear, while the second part considers erosion.

EXPERIMENTAL

Materials and deposition conditions. The obtained coatings, deposited by the HVOF technology using metal powder composites, include: the first group – coatings with tungsten matrix with notation – SX199/11 with average size of the powder particles 11 μm and SX199/45 with average size of the powder particles 45 μm. The second group includes coatings with nickel matrix with notation 1660-22/20 with average size of the powder particles 45 μm and coatings 1660-22/20 with average size of the powder particles 45 μm. The average size of the powder particles is denoted with Arabic numeral after the slash. Two samples have been made of each coating type and the results from the testing are taken on the average.

The coatings have been deposited on a carrier (substrate) of one and the same material – steel having the chemical composition shown in Table 1. The hardness of the substrate is 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	0.20	0.55	0.30	0.45	0.045	0.30	balance

The pretreatment of the substrate prior to the deposition of the coatings includes three steps: cleaning, blasting (erosion) and mechanical treatment.

The blasting is aimed at increasing the ruggedness of the surface to enhance the adhesion strength of the coating with the surface. The blasting represents erosion of the surface by means of a system having definite technical parameters. Abrasive material is used 'Grit' in accordance with the requirements of the standard ISO 11126 with grain size composition of the abrasive in mm in percentage 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 sizes below 0.15 mm various fractions – up to 100% of the following chemical compounds: SiO_2 – 41% , combined in the form of silicates; Al_2O_3 – 8.3%, MgO – 6.6%, CaO – 5.5% and MnO – 0.4%.

The technical parameters of the mobile system for blasting are the following: inlet pressure 8 atm; working pressure in the nozzle – 4 atm; diameter of the nozzle Φ – 7 mm; distance between the nozzle and the surface – 30 mm; angle of interaction of the jet with the surface – 90°.

The studied coatings have been deposited using a system model MICROJET+ Hybrid without any preliminary thermal treatment of the substrate (cold process).

The parameters of the technological regime of deposition of the coatings are represented in Table 2.

Table 2. Technological regime parameters for HVOF coating deposition

Parameter	Technological regime
Propylene/oxygen ratio	55/100%
Jet velocity	1000 m/s
Distance 'nozzle-coating'	100 mm
Angle between nozzle and coating	90°
Air pressure from compressor	5 bar
N_2 pressure in the proportioning device	4 bar
Velocity of powder material feeding	1.5 min^{-1}
Mass flowrate of the powder material	22 g/min

Table 3 represents the data for the notation, chemical composition (wt.%), average size of the powder particles in the composition and hardness of the studied coatings.

Table 3. Chemical composition, particle size and hardness of coatings

No	Coatings	Chemical composition (%)	Particle size (μm)	Hardness of coatings
1	SX199/11	Cr:21; WC-Cr_3C_2-Ni:6.1; C:5.8 W: Balance	11	HRC 64-66
2	SX199/45	Cr:21; WC-Cr_3C_2-Ni:6.1; C:5.8 W: Balance	45	HRC 62-64
3	1660-22/20	C:0.9; Si:4.3; B:3.3; Fe:4.2; Cr:16.3 Ni: Balance	20	HRC 58-60
4	1660-22/45	C:0.9; Si:4.3; B:3.3; Fe:4.2; Cr:16.3 Ni: Balance	45	HRC 57-59
5	Substrate: steel	C:0.15; Si:0.21; Mn:0.8; Ni:0.3; P:0.011; S:0.025; Cr:0.3	–	HRC 38-45

The coatings have been subjected to mechanical treatment – grinding and polishing to achieve identical ruggedness and equal thickness. The initial thickness of the coatings is 600 ± 0.8 μm, while the initial ruggedness is R_a = 0.430–0.435 μm.

The thickness of the coatings is measured by a portable device Pocket Leptoskop 2021 Fe (Fig. 1). The measurements have been made in 10 points on the surface and the mean arithmetic value is taken.

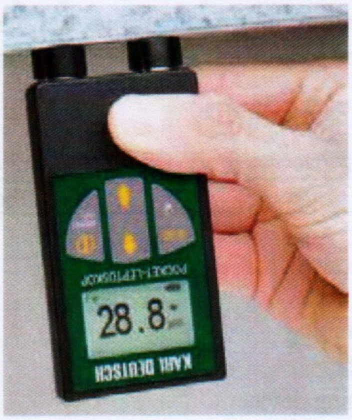

Fig. 1. Measuring of the thickness of the coatings with Pocket Leptoskop 2021

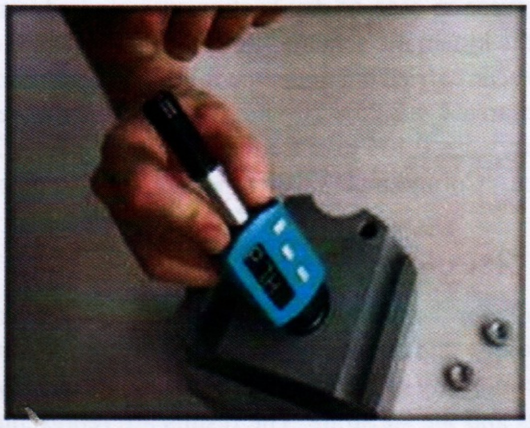

Fig. 2. Measuring of the hardness of the coatings with Bambino

The measurement of the hardness of the coatings has been done using hardness-metering device Bambino based on the scale of Rockwell (HRC) – Fig. 2. The hardness value has been estimated as mean arithmetic value out of three measurements for each sample in order to eliminate the possible effects of segregation and to obtain more realistic estimation for it.

Methodology. The methodology for studying the characteristics of abrasive wear consists of measuring the mass wear of the samples for a specific pathway of friction at permanently set dynamic regime and conditions of friction – loading, velocity of sliding, and type of abrasive, sizes of the samples. The mass of the samples before and after the friction is measured by electronic balance WPS 180/C/2 with an accuracy of 0.1 mg.

The wear rate γ_a represents the destroyed mass of the coating per 1 min, i.e.

$$\gamma_a = m/t \text{ (mg/min)}. \tag{1}$$

The specific wear intensity i is represented as the destroyed mass of the surface layer during the friction under normal loading $P = 1$ N, friction pathway $L = 1$ m and nominal contact area $A_a = 1$ mm^2:

$$i_a = m/(P\,L\,A_a) \text{ (mg/N m mm}^2\text{)}. \tag{2}$$

The specific wear resistance I_a is represented as the reciprocal value of the specific intensity and it is calculated using the formula:

$$I_a = 1/i_a = (P\,L\,A_a)/m \text{ (N m mm}^2\text{/mg)}. \tag{3}$$

The relative wear resistance $R_{i,j}$ represents the ratio between the wear resistance of the tested sample $I_{1,a}$ and the wear resistance of the sample, accepted as a standard $I_{j,a}$, determined under the same conditions of friction, i.e.

$$R_{i,j} = I_{i,a}/I_{j,a}. \tag{4}$$

The abrasive wear in case of dry friction was studied using the laboratory device following the kinematic scheme 'Pin-on-disk' in planar contact[7].

The study has been carried out under the following conditions: loading $P = 4.6$ N, nominal contact area $A_a = 2.25 \times 10^{-6}$ m²; nominal contact pressure $p_a = 2.04$ N/cm², sliding velocity – $v = 0.155$ m/s; frequency of rotation $n = 212$ min⁻¹, kind of the abrasive surface – Corundum P 320, temperature of the environment $T = 23$°C.

RESULTS AND DISCUSSION

Experimental results for the wearing characteristics have been obtained using the described methodology and the device for testing the abrasive wear – mass wear, wear rate, specific intensity of wearing off, absolute and relative wear resistance for all the coatings and the substrate. The results are represented respectively in Tables 4, 5, 6, 7 and 8.

Table 4. 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	SX199/11	0.3	0.6	1.3	2.4
2	SX199/45	13	20.2	27.1	33.2
3	1660-22/20	2.4	3.8	5.9	6.9
4	1660-22/45	7.0	12.3	15.9	18.5
5	Substrate: steel	10.3	15.1	18.2	20.5

Table 5. Wear rate of tested coatings

Sample	Coating designation	Number of cycles (N)			
		100	200	300	400
		Sliding distance (m)			
		20	40	60	80
		Friction time (min)			
		0.47	0.94	1.41	1.88
		Wear rate (mg/min)			
1	SX199/11	0.64	0.64	0.92	1.28
2	SX199/45	27.7	21.48	19.22	17.66
3	1660-22/20	5.11	4.04	4.18	3.67
4	1660-22/45	14.89	13.09	11.28	9.84
5	Substrate: steel	21.09	16.06	12.9	10.9

Table 6. Specific wear intensity of tested coatings

Sample	Coating designation	Number of cycles (N)			
		100	200	300	400
		Sliding distance (m)			
		20	40	60	80
		Specific wear intensity (mg/N m mm^2)			
1	SX199/11	0.1×10^{-4}	0.1×10^{-4}	0.2×10^{-4}	0.28×10^{-4}
2	SX199/45	6.28×10^{-4}	4.88×10^{-4}	4.36×10^{-4}	4.0×10^{-4}
3	1660-22/20	1.1×10^{-4}	0.9×10^{-4}	0.95×10^{-4}	0.83×10^{-4}
4	1660-22/45	1.16×10^{-4}	2.97×10^{-4}	2.56×10^{-4}	2.23×10^{-4}
5	Substrate: steel	4.97×10^{-4}	3.64×10^{-4}	2.93×10^{-4}	2.50×10^{-4}

Table 7. Wear resistance of tested coatings

Sample	Coating designation	Number of cycles (N)			
		100	200	300	400
		Sliding distance (m)			
		20	40	60	80
		Wear resistance (N m mm^2/mg)			
1	SX199/11	10×10^4	10×10^4	5×10^4	3.6×10^4
2	SX199/45	0.16×10^4	0.20×10^4	0.23×10^4	0.25×10^4
3	1660-22/20	0.91×10^4	1.1×10^4	1.1×10^4	1.2×10^4
4	1660-22/45	0.86×10^4	0.34×10^4	0.39×10^4	0.45×10^4
5	Substrate: Steel	0.20×10^4	0.27×10^4	0.34×10^4	0.40×10^4

Table 8. Relative wear resistance of tested coatings for friction path 80 m

Sample	Coating designation	Wear resistance for friction path 80 m	Relative wear resistance $R_{i,j}$	
			influence of particle size	influence of the coating on the substrate
1	SX199/11	3.6×10^4	$R_{1,2} = 14.1$	$R_{1,5} = 9.0$
2	SX199/45	0.25×10^4	$R_{2,2} = 1$	$R_{2,5} = 0.6$
3	1660-22/20	1.2×10^4	$R_{3,4} = 2.7$	$R_{3,5} = 3.0$
4	1660-22/45	0.45×10^4	$R_{4,4} = 1$	$R_{4,5} = 1.1$
5	Substrate: steel	0.40×10^4	–	$R_{5,5} = 1$

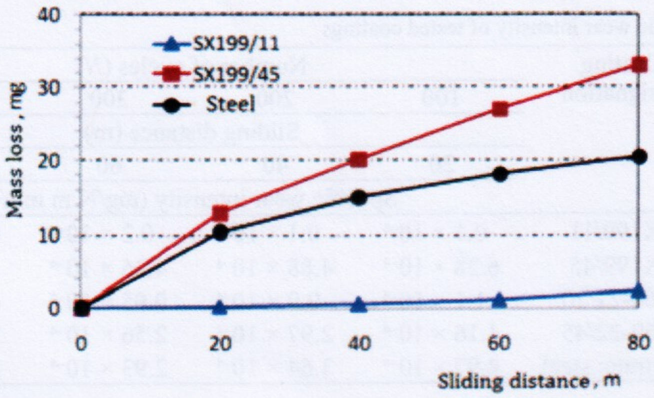

Fig. 3. Dependence of mass loss on friction path for composite coating with tungsten matrix

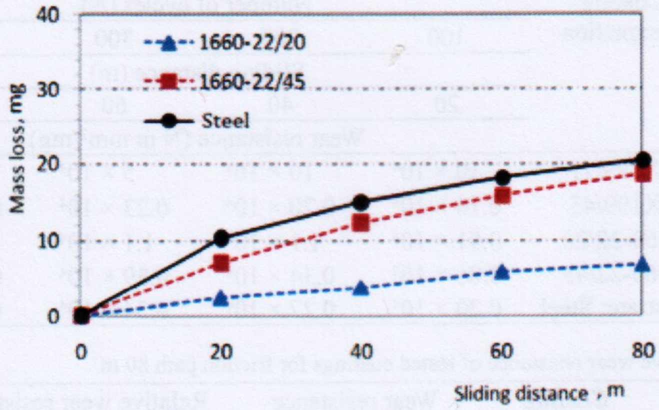

Fig. 4. Dependence of mass loss on friction path for composite coatings with nickel matrix

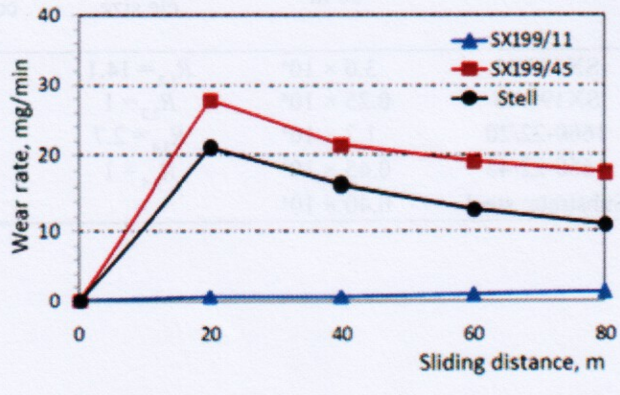

Fig. 5. Dependence of wear rate on friction path for composite coating with tungsten matrix

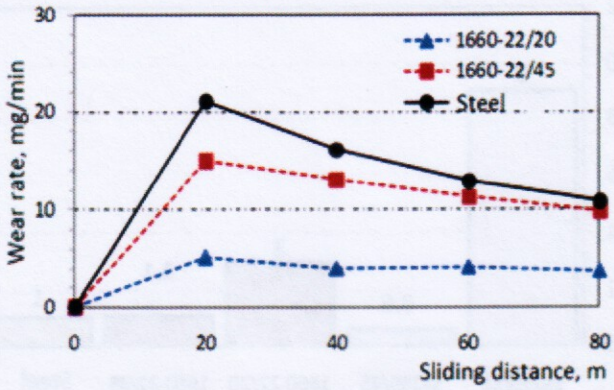

Fig. 6. Dependence of wear rate on friction path for composite coating with nickel matrix

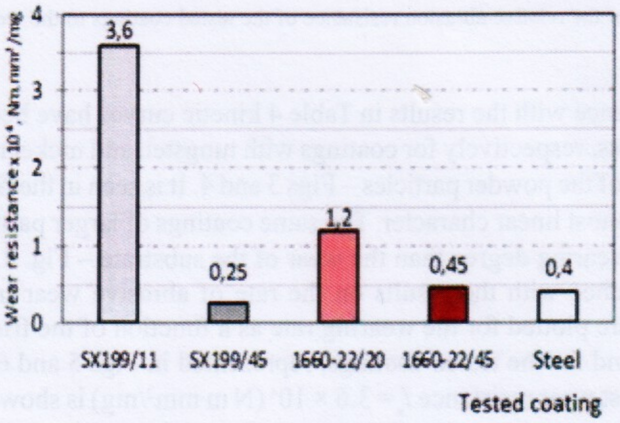

Fig. 7. Abrasion resistance chart of test coatings and substrate

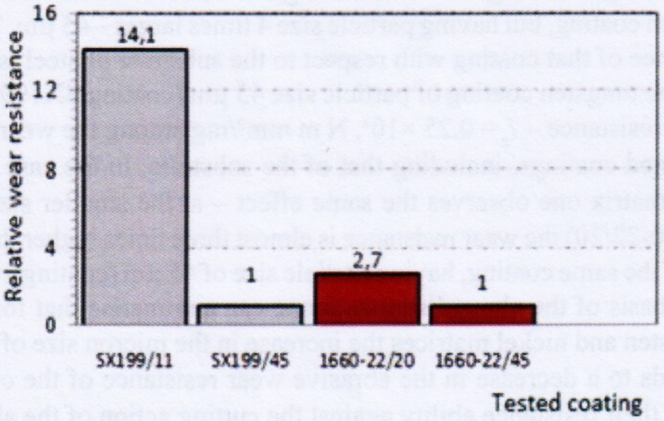

Fig. 8. Diagram of influence of particle size on the abrasion resistance of the tested coatings

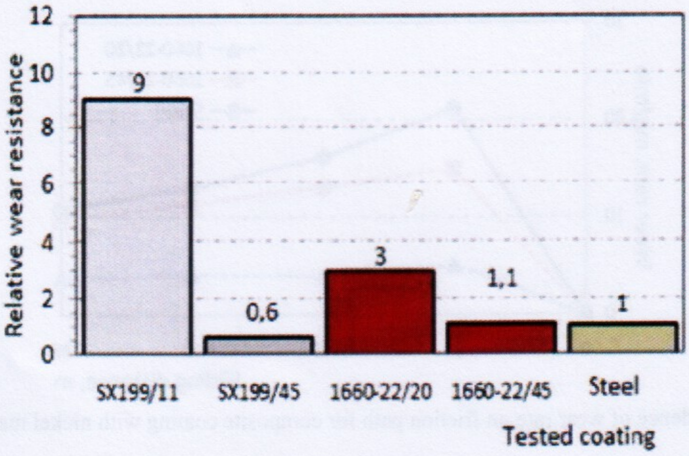

Fig. 9. Diagram of the relative abrasion resistance of the tested coatings to the wearing resistance of the substrate

In accordance with the results in Table 4 kinetic curves have been plotted for the wear process, respectively for coatings with tungsten and nickel matrix having different sizes of the powder particles – Figs 3 and 4. It is seen in the figures that the curves have almost linear character. The same coatings of larger particles – 45 μm show greater wearing degree than the wear of the substrate – Fig. 3.

In accordance with the results on the rate of abrasive wear in Table 5 the dependences are plotted for the wearing rate as a function of the friction path for the substrate and for the tested coatings, represented in Figs 5 and 6.

The highest wear resistance $I_a = 3.6 \times 10^4$ (N m mm^2/mg) is shown by the coating with tungsten matrix (coating SX199/11) of particle size 11 μm (Fig. 7), which is an order of magnitude higher – 14.1 times greater than the wear resistance of the same tungsten coating, but having particle size 4 times larger – 45 μm. The relative wear resistance of that coating with respect to the substrate of steel is 9 (Fig. 9).

The same tungsten coating of particle size 45 μm (coating SX199/45) has the lowest wear resistance – $I_a = 0.25 \times 10^4$, N m mm^2/mg among the wear resistances of all the tested coatings, including that of the substrate. In the case of coatings with nickel matrix one observes the same effect – at the smaller size of 20 μm (coating 1660-22/20) the wear resistance is almost three times higher than the wear resistance of the same coating, having particle size of 45 μm (coating 1660-22/45).

On the basis of the above listed data one can summarise that for both coatings of tungsten and nickel matrices the increase in the micron size of the powder particles leads to a decrease in the abrasive wear resistance of the coatings, i.e. reduction of their resistance ability against the cutting action of the abrasive particles during friction.

CONCLUSIONS

The present research work, which consists of two separate parts, reports comparative studies of the wearing characteristics and the wear resistance of composite powder coatings, deposited by means of High Velocity Oxygen-Fuel (HVOF) spraying technology. Two groups of coatings have been prepared, consisting of powder compositions of tungsten and nickel matrix, whereupon each group includes coatings of different micron sizes of the powder particles.

In the present first part of the research work the coatings have been tested for wear degree under identical regimes of dry friction on the surface with attached abrasive particles under the same conditions. Results have been obtained as well as dependences for mass wearing off, wear rate and wear intensity, absolute and relative abrasive wear resistance.

It has been shown that the dependence of mass abrasive wear on the friction path length has a non-linear character. It has been found out that the reduction of the size of the powder particles in the compositions leads to increase in the wear resistance of the coatings with tungsten and nickel matrices. Greater effect of the influence of the particle sizes has been found out in the case of the coatings with tungsten matrix.

The highest wear resistance is shown by the coatings with tungsten matrix with the size of the powder particles 11 μm, which is one order of magnitude (14.1 times) higher than the wear resistance of the same coating having particle size of 45 μm.

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