

WEAR OF GAS-FLAME COMPOSITE COATINGS WITH TUNGSTEN AND NICKEL MATRIX. PART II. EROSIVE WEAR

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Abstract. The object of the investigation is characterising the wear and wear resistance of composite powder coatings, deposited by supersonic flame stream (i.e. High Velocity Oxygen-Fuel (HVOF) spraying). Two groups of coatings have been obtained – powder composites of tungsten and nickel matrices, whereupon each group includes coatings having different sizes of the powder particles. The coatings have been tested in two cases – during abrasion and erosion. The research work consists of two parts. The first part represents the results on the characteristics of wear during dry friction on the surface with fixed attached abrasive particles. Results are presented here on the wearing of the coatings under the effect of air stream, carrying solid abrasive particles (erosion wear), more specifically – mass erosion wear, erosion rate, erosion intensity, absolute and relative wear resistance under identical conditions of erosion of the coatings. It has been found out that upon increasing the size of the particles 4 times from 11 to 45 μm in the case of coatings with tungsten matrix the wear resistance grows up 2.1 times, while in the case of coatings with nickel matrix the growth of the erosion resistance is insignificant – 1.2 times. The comparative results on the wear of the tested coatings during abrasion and erosion show different tendencies in the influence of the sizes on the wear and wear resistance. The abrasive wear resistance of the two kinds of coatings is greater in the case of smaller sizes of the powder particles. The same coatings in the case of erosion possess lower wear resistance, i.e. lower resistant ability under the impact effect of the abrasive particles in the air stream.

Keywords: HVOF coatings, tribology, abrasion wear, erosive wear.

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AIMS AND BACKGROUND

The green tribology is a new interdisciplinary scientific research direction within the functional space of the tribology, directed to stable development of the society 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'. In its popular type it is connected basically with the aspiration to minimise the pollution of the environment and the risks for the health by using lubricating materials, techniques and technologies, connected with the reduction of friction and wear degree¹⁻⁵.

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. It is connected with carrying out a complex of investigations and elaboration of interdisciplinary technologies, which guarantee functionality, effectiveness and stable development of the system 'society-environment'¹⁻⁵.

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 characteristics⁶⁻¹¹.

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. HVOF is accepted as one of the innovation technologies for preparing functional coatings with unique exploitation characteristics – high density, stability to corrosion, wear resistance and others under extreme conditions of exploitation – abrasion, erosion, high temperatures, active corrosion medium, and vibrations. In many countries in Europe and North America, as well as in Russia, in many branches of the industry the HVOF deposition has practically replaced the galvanic and vacuum methods for deposition of coatings. The HVOF-coatings exceed considerably the highly wear resistant coatings, containing industrial chromium, obtained by highly toxic and in many cases carcinogenic galvanic methods⁷⁻¹³.

The operating process in the supersonic flame stream burner for deposition of HVOF-coatings is analogous to the working process in a rocket engine⁹. The powder compositions, known in the specialised literature as powder super alloys, represent composites of particles of different metals, alloys, ceramics, and polymeric materials. The particles, carried by the flame stream, pass over to plastic and/or semi-plastic state in the form of particle or drop and after the contact with the substrate they are being deformed forming thin lamellas. Upon collision with surface irregularities the particles-droplets are cooling down, forming adhesion

and cohesion contact bonds with the basic surface and between themselves thus forming laminar structure of the composite coating. The preparation of coatings of high adhesion, compactness, density, low porosity, lack of oxides is a complex multi-factorial process, which is the object of continuous investigations and improvements. 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 substrate¹³⁻²².

The object of the present research work is determination of 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.

EXPERIMENTAL

The obtained coatings, deposited by the HVOF technology using metal powder composites, were prepared according to the conditions described in Ref. 1.

The chemical conditions and the technological regime were described in our previous paper in the same field¹. In this paper¹ are given also the chemical, particle size and the hardness of the coatings produces.

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

The measurement of the hardness of the coatings was done using a hardness-metering device Bambino based on the scale of Rockwell (HRC) (Ref. 1).

DEVICE AND METHODOLOGY

Erosive wear tests were carried out on jet nozzle type erosion equipment (Fig. 1) in the ambient air, at room temperature. This testing utilises repeated gas-entrained solid particle impingement erosion, and involves a small nozzle delivering a stream of gas containing solid particles which impacts the surface of a test specimen.

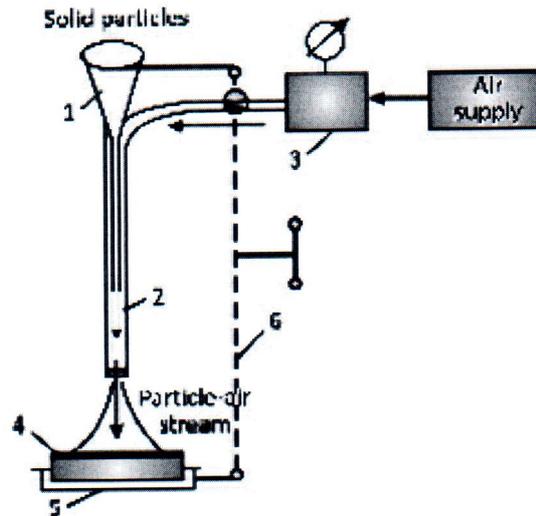


Fig. 1. Schematic diagram of erosive wear testing

Solid particles are poured from the reservoir (1) by freefalling to the nozzle tube (2). Length of the nozzle is 200 mm, diameter is 8 mm, and exit diameter is 6 mm. Before the tests, solid particles material was sieved through a set of sieves and dried in an oven for removal of moisture from the particles. The air stream was provided by the compressed air at controlled pressure, purified from particles and moisture (3). Air stream also enters the nozzle tube (2), where the formation of two-phase (particle-air) working stream takes place. The test sample (4), in the rectangular shape (20 × 25 mm) and 3 mm thickness, is fixed in a holder (5) attached to the reversing mechanism (6). With reversing mechanism (6), two working parameters are controlled: (a) distance of the sample from the nozzle, and (b) impact angle of the particles. Parameters used in the erosive wear testing (solid particles material, maximum size of the particles, air stream pressure, particles flow, particles impact angle, distance between the sample and the nozzle and duration of the test) were the same for all tested coatings¹.

The mass flow rate \dot{m}_a of a given abrasive material with mass m_a in the device is determined by measuring the time t_a for the gravitational flowing out of the abrasive material. It is calculated by the formula:

$$\dot{m}_a = m_a/t_a. \quad (1)$$

A minimum of 3 measurements were carried out and the mean arithmetic value was estimated.

The methodology for studying the erosion wear and wear resistance by means of the described device consists of measuring the mass of the sample before stream treatment and its mass after exposure to treatment with two-phase stream under the same fixed parameters: distance l , angle of interaction α , working pressure P , type and average size of the abrasive particles, mass flow rate of the abrasive material \dot{m}_a . The difference in the mass of the sample before and after the treatment

represents the mass erosion wear – m (mg). The rate of erosion wear is determined by the following formula:

$$\dot{m} = m/t_e, \quad (2)$$

where t_e is the time duration of the treatment of the coating.

The intensity of the erosion is determined by the formula:

$$i_e = \dot{m}/\dot{m}_a, \quad (3)$$

The intensity of the erosion i_e represents the ratio between the rate of mass wear of the surface layer and the mass flow rate of the abrasive phase in the stream. The intensity of the erosion is a non-dimensional number.

The erosion wear resistance I_e is defined as the reciprocal value of the intensity of erosion. It represents a non-dimensional number, which shows how many grams of the abrasive mass m_a is needed for the loss per 1 of mass m from the surface of the sample for a definite period of time of the interaction, i.e.

$$I_e = 1/i_e = \dot{m}_a/\dot{m}. \quad (4)$$

The relative erosion wear resistance $R_{i,j}$ is determined by the formula:

$$R_{i,j} = I_i/I_j, \quad (5)$$

where I_i is the erosion wear resistance of the tested sample, determined using (4), while I_j – the wear resistance of a sample, accepted as a standard for comparison, evaluated under the same conditions of wearing.

The relative erosion wear resistance $R_{i,j}$ is a dimensionless number, which shows what is the share of the wear resistance of the tested sample related to the wear resistance of the standard under identical conditions of stream-abrasive erosion.

The samples of the tested coatings and the substrate have the form of a parallelepiped of dimensions $25 \times 30 \times 5$ mm.

The parameters of the erosion using two-phase air-abrasive stream are represented in Table 1.

Table 1. Parameters used in erosive wear testing

Test parameter	Value
Solid particles material	black corundum (Al_2O_3)
Maximum size of the particles	600 μm
Air stream pressure	0.1 MPa
Particles flow	166.67 g/min
Particles impact angle	90°
Distance between the sample and the nozzle	10 mm
Duration of the test	5 min
Ambient temperature	24°C

RESULTS AND DISCUSSION

Results have been obtained using the above described device and the methodology for testing in the case of stream-abrasive erosion with respect to mass wear, rate and intensity of wearing off process, the absolute and relative erosion wear resistance of all the tested coatings and the substrate. These results are listed in Tables 2 and 3.

Table 2. Erosive wear of tested coatings

Sample	Coating designation	Mass loss (mg)	Wear rate (mg/min)	Intensity of erosion	Wear resistance to erosion
1	SX199/11	23.3	4.66	2.33×10^{-5}	4.3×10^4
2	SX199/45	11.0	2.20	1.1×10^{-5}	9.0×10^4
3	1660-22/20	13.3	2.66	1.33×10^{-5}	7.5×10^4
4	1660-22/45	11.6	2.32	1.16×10^{-5}	8.6×10^4
5	substrate: steel	58.6	11.72	5.86×10^{-5}	1.7×10^4

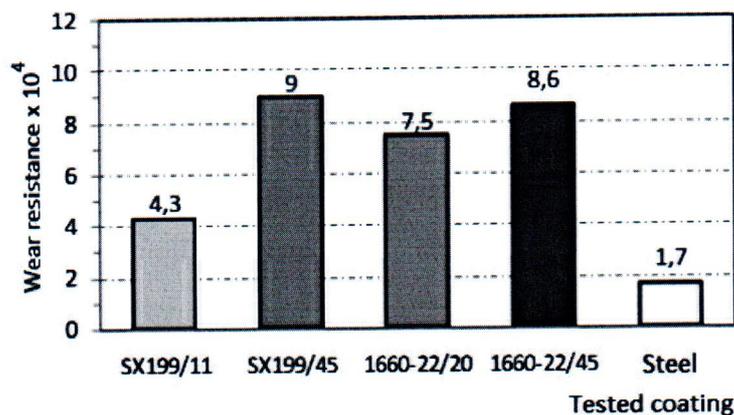


Fig. 2. Diagram of erosion wear resistance of the tested coatings and the substrate

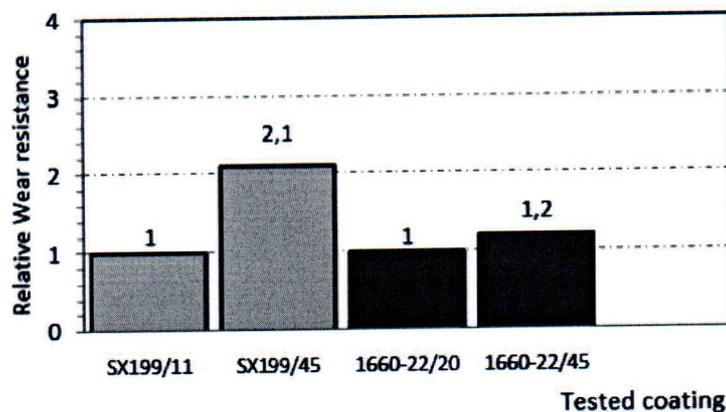
It is seen in the diagram of erosion wear resistance of the samples, represented in Fig. 2 that the highest wear resistance during erosion is shown by the coatings with tungsten matrix with particles size 45 μm . The decrease in the sizes of the particles – 11 μm leads to lowering of the erosion wear resistance. This result is the opposite of the result for abrasive wear resistance. The lowest wear resistance during erosion is shown by the substrate, i.e. steel without any coating.

Table 3. Relative wear resistance

Sample	Coating designation	Wear resistance	Relative wear resistance	
			influence of the size of the particles	overall impact of the coating
1	SX199/11	4.3×10^4	$R_{1,1} = 1$	$R_{1,5} = 2.53$
2	SX199/45	9.0×10^4	$R_{2,1} = 2.1$	$R_{2,5} = 5.29$
3	1660-22/20	7.5×10^4	$R_{3,3} = 1$	$R_{3,5} = 4.41$
4	1660-22/45	8.6×10^4	$R_{4,3} = 1.2$	$R_{4,5} = 5.05$
5	substrate: steel	1.7×10^4	–	$R_{5,5} = 1$

Upon increasing the size of the particles 4 times from 11 to 45 μm in the case of coatings with tungsten matrix the wear resistance grows up 2.1 times, while in the case of coatings with nickel matrix the increase in the erosion wear resistance is insignificant – 1.2 times (Table 3, Fig. 2).

The increase in the wear resistance of the coatings with respect to the wear resistance of the substrate can be seen in the data in the last column of Table 3 and in the diagram of Fig. 4. The greatest effect of increase in the wear resistance is obtained with both types of coatings – with the tungsten and with the nickel matrices having sizes of the powder particles 45 μm . The increase in the wear resistance for these coatings is very close in value, respectively 5.29 and 5.05 times.

**Fig. 3.** Diagram of the effect of particle size on the erosion wear resistance of the tested coatings

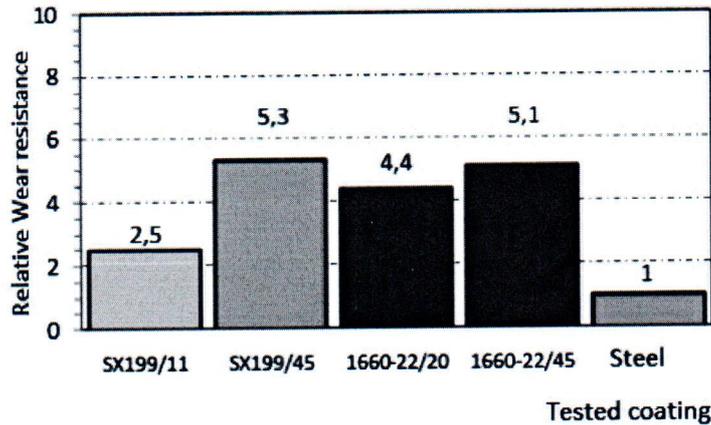


Fig. 4. Diagram of the relative erosion resistance of the tested coatings to the wearing resistance of the substrate

COMPARATIVE RESULTS OF ABRASION AND EROSION WEAR RESISTANCE OF THE COATINGS

Table 4 represents the results on abrasion and erosion wear resistance of the tested gas-flame coatings.

Table 4. Comparative results of the wear resistance of coatings when abrasion and erosion

Sample	Coating designation	Abrasion wear resistance, I_a	Erosion wear resistance, I_e	$W_{e,a} = I_e/I_a$
1	SX199/11	3.6×10^4	4.3×10^4	1.19
2	SX199/45	0.25×10^4	9.0×10^4	36.00
3	1660-22/20	1.2×10^4	7.5×10^4	6.25
4	1660-22/45	0.45×10^4	8.6×10^4	19.11
5	substrate: steel	0.4×10^4	1.7×10^4	4.25

It is clearly seen that in the case of abrasion wear the observed wear resistance of the two types of coatings is greater when the sizes of the powder particles are smaller, respectively for the coatings with the tungsten matrix of 11 μm and for the coatings with nickel matrix of 20 μm . The same coatings during erosion have lower wear resistance, i.e. lower resisting ability in the case of impact action of the abrasive particles in the air stream.

In general we can conclude that the wear resistance of the tested coatings and that of the substrate is greater during erosion in comparison to that during abrasive friction. The comparative results are represented in the last column of Table 4. Under exploitation conditions of the machine details in the presence of impact action of solid state particles (erosion) more appropriate are the coatings with tungsten and nickel matrices of dimensions of the powder particles 45 μm .

At this stage of the investigation one is not able to give a categorical explanation and interpretation of these facts in view of missing information about the density and the microstructure of the coatings before and after the wearing off process.

CONCLUSIONS

The present research work reports carrying out comparative investigations of the characteristics of wearing and wear resistance of composite powder coatings, deposited by means of HVOF technology. Two groups of coatings have been prepared – powder compositions of tungsten and nickel matrices, whereupon each group includes coatings of different micron dimensions of the powder particles.

A device has been elaborated as well as a methodology for studying the characteristics of erosion wear under the effect of air stream, carrying solid abrasive particles. The methodology is in accordance with the present days standards.

Results have been obtained about mass erosion wear, rate and intensity of the erosion, absolute and relative erosion wear resistance under identical conditions of erosion of the coatings.

It has been established that upon increasing the size of the particle 4 times within the range from 11 to 45 μm in the case of coatings with tungsten matrix the wear resistance grows up 2.1 times, while in the case of coatings with nickel matrix the increase in the erosion wear resistance is insignificant – 1.2 times.

The comparison of the results about the wearing of the tested coatings during abrasion and erosion show opposite tendencies of the influence of the sizes on the wearing off process and on the wear resistance. The abrasion wear resistance of the two kinds of coatings is greater when the sizes of the powder particles are smaller. The same coatings during erosion have lower wear resistance, i.e. lower resisting ability with respect to impact action of the abrasive particles in the air stream. These results are not surprising taking into consideration the different mechanisms through which the different processes of abrasion and erosion are occurring. During the abrasion the specificity is the single mechanical impacts under the effect of tangential forces of interaction between the particles and the surface of the coating, while during the erosion the surface is subjected to multiple impacts of the solid particles, whereupon with the course of time some exhaustion processes are occurring and respectively destruction. It is possible that the destruction of the surface layer by single impacts of the particle, which is occurring in the extreme case with fragile materials^{1,2,23,24}.

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