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EFFECT OF THE ANGLE OF INCIDENCE OF ABRASIVE PARTICLES ON THE EROSIVE WEAR RESISTANCE OF HVOF-SPRAYED COMPOSITE COATINGS

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ABSTRACT

The study presents test results concerning resistance to impingement erosion caused by solid particles transported in the gas stream. The angle at which the erosive jet affected the HVOF-sprayed coatings made using the Ni–WC flux-cored wire amounted to 30° and 90°. The study included microhardness measurements and the microscopic metallographic specimens of the deposited (sprayed) coatings.

KEY WORDS: thermal spray, wire-high-velocity oxy-fuel (W-HVOF), erosion, flux cored wire

High-quality erosive wear resistant coatings can be obtained using processes where particles of deposited materials are accelerated to supersonic velocity (e.g. the high velocity oxy fuel process (HVOF)). Presently, HVOF process-related tests are primarily concerned with coating formed through the melting of the coating material in the form of powder. In comparison with the powder, the coating material in the form of a wire is cheaper to manufacture and can be sprayed at higher deposition rates [1, 3, 8, 10].

Erosive wear processes reduce the service life of various machinery parts. In industry, erosion is estimated to be responsible for the wear of approximately 8 % of machine elements. Welding technologies enable the deposition of erosion-resistant coatings and layers [4, 9, 10].

The intensity of the erosive wear of sprayed coatings depends, among other things, on the angle of incidence of abrasive particles. In erosion resistance tests, composite Ni–WC coatings may demonstrate the unequal loss of volume in relation to the extreme angles of incidence of the erosive jet. Available reference publications present test results concerning the erosive wear resistance of HVOF powder sprayed coatings. However, related publications do not contain quantitative data making it possible to compare the intensity of the erosive wear of HVOF-sprayed coatings (deposited using the composite wire) in relation to various impact angles of abrasive particles. The above-named lack of information inspired an attempt to identify the effect of the angle of incidence of the erosive jet on the erosive wear resistance of HVOF-sprayed coatings deposited using the wire [1, 2, 6, 7, 10].

The study presents test results concerning resistance to impingement erosion triggered by solid particles contained in the gas jet striking the surface at an angle of 30° and 90°. The HVOF-sprayed coatings (made using an Ni–WC flux-cored wire) used in the tests had various thicknesses. The scope of the tests also included microhardness measurements and microscopic metallographic tests of deposited coatings.

Test materials. The HVOF spraying process involved the use of a HARDFACE NICARBW flux-cored wire (manufactured by Welding Alloys company) having a diameter of 2.4 mm, providing the obtainment of composite weld deposit containing particles of tungsten carbide in the nickel alloy matrix (group Ni20 in accordance with PN-EN 14700:2014-06). The core of the wire contained cast and crushed irregularly-shaped particles of tungsten carbide sized restricted within the range of 150 to 350 μm. The mass content of tungsten carbide particles in the wire amounted to 50 %. Recommendations concerning the use of the HARDFACE NICARBW wire include the cladding of surfaces exposed to intense erosive wear. According to the manufacturer, the wire can also be used in arc spraying [11]. The base material used in the tests had the form of specimens (75×25×15 mm) cut out of a plate made of unalloyed steel S355JR (according to PN-EN 10025-2:2019-11).

Tests. *Erosive wear resistance tests.* The tests, aimed to identify the significance of differences in the erosive wear resistance of coatings in relation to various angles of incidence (of abrasive particles), were performed using the Student's *t*-test, adopting significance level $\alpha = 0.05$. The thicknesses of the coatings amounted to approximately 100, 200 and 300 μm.

Table 1. Parameters used in the spraying of coatings

Oxygen flow rate, l/min	Propane flow rate, l/min	Air flow rate, l/min	Wire feed rate, cm/min	Spraying distance, mm
180	40	500	46,0	150

The tests of erosive wear resistance were performed in relation to two impact angles 30° and 90° respectively. The study involved the performance of 6 erosive wear resistance tests in relation to each coating thickness and each angle of incidence. Before spraying, the specimens were subjected to dry abrasive grit blasting. The HVOF spraying process was carried out using the Metatherm HVOF-W1000 system manufactured by Metatherm Verschleißschutz GmbH company. In this system, the wire is continuously feeding into the propane/oxygen flame. The droplets created from wire, are deposited to the prepared substrate with compressed air [12]. The technological parameters used when making the coatings are presented in Table 1.

The tests concerning resistance to erosion resulting from the impingement of solid particles in the gas jet were performed in accordance with the ASTM G76-18 standard using abrasive particles (Al_2O_3) having a nominal size of 50 μm. During the tests, the feed rate of the abrasive particles amounted to 2.2 g/min, whereas their velocity in the compressed air jet amounted to approximately 70 m/s. The nozzle tube was located 10 mm away from the specimen surface. The time of each test amounted to 10 minutes. The identification of the erosive wear resistance of the coatings involved measurements concerning the loss of mass and density. Before and after each test, specimens were weighed using a laboratory balance with an accuracy of up to 0.0001 g. Measurements of coating density involved one specimen representing a given coating thickness. The average coating density was determined using the laboratory balance on the basis of three measurements of the density of a given coating, weighed in air and in liquid. The loss of volume was determined (using formula (1)) on the basis of the loss of mass and the average density of a given coating. Related results are presented in Table 2.

$$V_1 = \frac{M_1}{\rho} \cdot 10^3, \quad (1)$$

where V_1 — loss of coating volume, mm³; M_1 — loss of specimen mass, g; ρ — coating density, g/cm³.

In accordance with the concept of the Student's *t*-test, first it was necessary to verify if erosion resistance-related test results were characterised by normal distribution and whether their variances were the same. The hypothesis of the normal distribution of the test results was verified using the Shapiro–Wilk test, adopting significance level $\alpha = 0.05$. In addition to the volume losses of in relation to the coating having a thickness of approximately 200 μm and an incidence angle of 90°, calculated values of W_d were restricted within the range, the ends of which were quantiles of distribution. In relation to the above-presented test results there was no basis for rejecting the hypothesis of the normal distribution in relation to a significance level of 0.05. Because of the assumptions of the Student's *t*-test, further analysis only involved groups of erosion test results characterised by normal distribution. The hypothesis of the equality of the variances

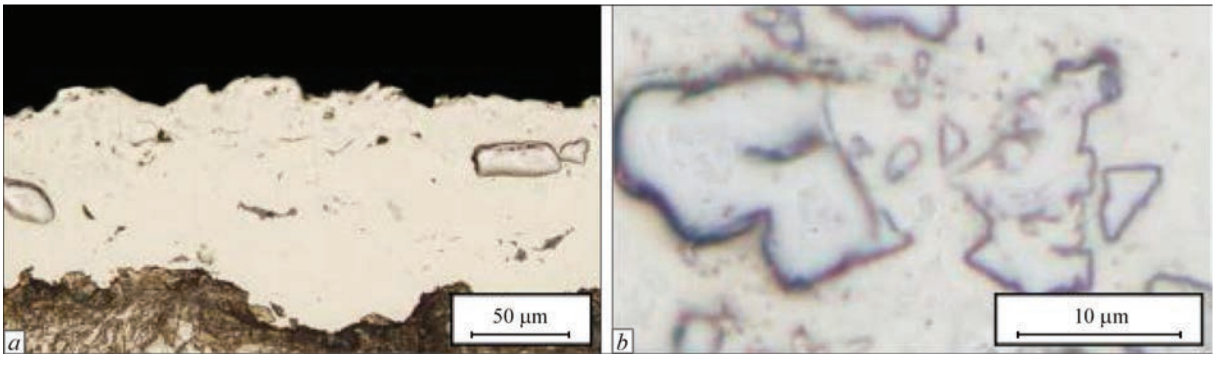
Table 2. Test results concerning the erosive wear resistance of the HVOF-sprayed coatings made using the Ni–WC flux-cored wire

Coating thickness, μm	Loss of coating volume, mm³						
	1	2	3	4	5	6	Average value for individual levels
Approx. 100	0.2935*; 0.2348**	0.2054*; 0.3131**	0.2837*; 0.3620**	0.3815*; 0.3033**	0.3522*; 0.2837**	0.3033*; 0.2739**	0.3033*; 0.2951**
Approx. 200	0.3252*; 0.3153**	0.3449*; 0.3350**	0.2365*; 0.3547**	0.3941*; 0.2168**	0.3350*; 0.3843**	0.3449*; 0.3646**	0.3301*; 0.3285**
Approx. 300	0.3467*; 0.2674**	0.3764*; 0.3764**	0.2972*; 0.3665**	0.3071*; 0.2476**	0.2774*; 0.4061**	0.3665*; 0.2278**	0.3286*; 0.3153**
In relation to all results							0.3206*; 0.3130**

*In relation to an incidence angle of 30°.
**In relation to an incidence angle of 90°.
The loss of the volume of sprayed coatings was identified using formula (1). The density of the coating having a thickness of approximately 100 μm amounted to 10.2219 g/cm³; that having a thickness of 200 μm amounted to 10.1487 g/cm³ and that having a thickness of 300 μm amounted to 10.0954 g/cm³.

Table 3. Microhardness results (*HV*0.1) related to the cross-section of the HVOF-sprayed coatings made using the Ni–WC flux-cored wire

Coating thickness, μm	Point of measurement of coating matrix microhardness			Average microhardness of coating matrix, *HV*0.1	Point of measurement of tungsten carbide microhardness in the coating			Average microhardness of tungsten carbides in the coating, *HV*0.1
	1	2	3		4	5	6	
Approx. 100	398	299	375	357	2107	1834	1660	1867
Approx. 200	443	386	324	384	1842	1917	1685	1815
Approx. 300	361	458	346	388	1707	1774	2116	1866



Microstructure of deposited coatings having a thickness of approximately: *a* — 100 μm, mag. ×400; *b* — 200 μm, mag. ×1000

of groups of erosive wear resistance test results was verified using the Hartley test. As the calculated values of H_{calc} were not restricted within the critical set in relation to a significance level of 0.05, there was no basis to reject the hypothesis subjected to verification. The calculated value of the Student's *t*-test was lower than the critical value $t_{0.05;\,10}$ of the aforesaid test. Because of the foregoing, it can be stated that the volume loss values obtained in the tests concerning the erosive wear resistance of coatings of given thicknesses did not differ significantly in terms of the angle of incidence (30° and 90°) of the erosive jet.

Microhardness measurements. The microhardness of the coatings sprayed using the Ni–WC wire was measured using the Vickers hardness test performed in accordance with the PN-EN ISO 6507-1:2018-05 standard. The cross-section of one specimen representing a given thickness of the coating was subjected to 3 measurements concerning the microhardness of the matrix and the microhardness of tungsten carbides. The obtained microhardness test results are presented in Table 3.

Metallographic tests. The identification of the quality and the porosity of the coatings as well as the content of the reinforcing phase and the size of its particles required the performance of microscopic metallographic tests. The metallographic tests of selected coatings involved the use of a light microscope and cross-sectional metallographic specimens. The results of the metallographic test results are presented in Figure *a* and *b*. The computer-aided analysis of the images of the specimen microstructure enabled the determination of coating porosity (Table 4) as well as the volume fraction and the geometrical dimensions of tungsten carbide particles.

The distribution of tungsten carbides in the coatings was not uniform. The measured content of tungsten carbides in the coatings did not exceed 33.3 % by volume, whereas their size was restricted within the range of approximately 1 to 62 μm.

Analysis of test results. The test results concerning the erosive wear resistance of the coatings deposited using the Ni–WC flux-cored wire revealed that, regardless of the coating thickness and the angle of erosive jet incidence, the coatings were characterised by high erosion resistance. The average loss of coat-

Table 4. Test results related to the porosity of the HVOF-sprayed coatings made using the Ni–WC flux-cored wire

Coating thickness, μm	Coating porosity, %
Approximately 100	2.0
Approximately 200	2.6
Approximately 300	2.9

ing density as regards individual coating thicknesses (determined in the test based on the ASTM G76-18 standard) was restricted within the range of 0.3033 to 0.3301 mm^3 in relation to an incidence angle of 30° and within the range of 0.2951 to 0.3285 mm^3 in relation to an incidence angle of 90°.

The tests aimed to determine the significance of differences in erosive wear resistance in relation to various angles of incidence (of abrasive particles) involved the use of the Student's *t*-test statistics. In relation to adopted level of significance $\alpha = 0.05$, in terms of the coatings having a thickness of approximately 100 and that of 300 µm, the calculated values of the Student's *t*-test were lower than critical value $t_{0,05;\ 10}$ of the aforesaid test. Therefore, it can be stated that volume loss values obtained in the erosive wear resistance tests of coating thicknesses in relation to related angles of erosive jet incidence (30° and 90°) did not differ significantly. The foregoing could probably be ascribed to the composite structure of the coating (hard particles of tungsten carbide in the relatively soft nickel alloy matrix) affected by two models of wear, i.e. brittle cracking (reinforcing elements) and plastic deformation (matrix) [6]. It should be emphasized that the volume losses identified in the erosive wear resistance tests are not a permanent material feature as they may change along with changes of related parameters [5, 10]. The low porosity of the sprayed coatings, restricted within the range of 2.0 to 2.9 %, favours the lower intensity of erosive wear [10].

The average values of the microhardness of the matrix in individual coatings were restricted within the range of 357 *HV*0.1 to 388 *HV*0.1, whereas the microhardness range in relation to a given coating thickness was between 99 *HV*0.1 and 119 *HV*0.1. The cross-sectional microhardness of tungsten carbide particles was restricted within the range of 1660 *HV*0.1 to 2116 *HV*0.1.

The microscopic metallographic tests did not reveal the separation of the coating from the substrate or the presence of cracks in the coating in any of the analysed variants of coating thickness. The arrangement of tungsten carbides in the coating was not uniform. The size of tungsten carbide particles in the coating was restricted within the range of approximately 1 to 62 µm. The highest identified content of tungsten carbide particles amounted to 33.3 % by volume. The above-named value was lower than the volume fraction of tungsten carbide grains contained in the core of the flux-cored wire used in the spraying process. The most probable reasons for the decrease in the content of tungsten carbide particles in the coating include their dissolution during the spraying process, directing the particles outside the surface being coated as well as the reflection of the particles against the substrate or their improper deposition in the coating.

CONCLUSIONS

The tests concerning the properties of HVOF-sprayed composite coatings made using the Ni20 flux-cored wire justified the formulation of the following conclusions:

1. The values of volume losses identified in the erosive wear resistance tests of the coatings in relation to an erosive jet angle of 30° and that of 90° did not differ significantly.
2. The average microhardness of the coating matrix was restricted within the range of 357 *HV*0.1 to 388 HV0,1, whereas the average microhardness of the tungsten carbide particles was restricted within the range of 1815 *HV*0.1 to1867 *HV*0.1.
3. The arrangement of tungsten carbides in the deposited coatings was not uniform. The measured content of tungsten carbide particles in the coatings did not exceed 33.3 % by volume, which indicated the lower amount of tungsten carbides in the coating than that in the composite material which was used to make the coatings. The size of tungsten carbide particles in the coatings was restricted within the range of approximately 1 to 62 µm. Regardless of the thickness of the coatings, their porosity did not exceed 2.9 %.

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