COMPARISON OF ABRASIVE WEAR RESISTANCE OF ARC-SPRAYED AND HVOF-SPRAYED COATINGS AS WELL AS OVERLAY WELDS MADE USING SELF-SHIELDED FLUX-CORED WIRE

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https://doi.org/10.37904/metal.2023.4723

Abstract

The article presents results of tests concerning the metal-mineral abrasive wear resistance of arc-sprayed coatings with lower and higher air pressure (larger and smaller drops of metal) and HVOF-sprayed coatings deposited using the self-shielded flux cored wire providing the obtainment of the weld deposit of high-chromium cast iron Fe15 (in accordance with EN 14700). The significance of influence of the spraying technologies on abrasion resistance was determined using a completely randomized design. The scope of tests also included the analysis of the chemical and phase compositions as well as the microscopic metallographic tests of deposited (sprayed) coatings. For comparison, analogous tests were carried out for the overlay welds applied by self-shielded flux cored arc surfacing using the same flux cored wire.

Keywords: Thermal spray, hardfacing, abrasion, arc spraing, wire-high-velocity oxy-fuel (W-HVOF)

1. INTRODUCTION

The wear of equipment and machinery parts restricts their service life. Loss of functional properties of key elements can lead to downtime of the entire production line. Production down times are associated with the need to incur losses, e.g. resulting from the loss of production capacity. In order to extend the service life of machines without failure, materials with greater wear resistance are used. A thin zone of the surface layer is responsible for the intensity of abrasive wear, which can be shaped by surfacing technologies (e.g. thermal spraying, technologies which incorporate a welding process) [1-7].

The abrasion resistance depends primarily on a surfacing technology, which is related to the type of a surfacing material. Coatings (layers) made with different surface engineering technologies with the same surfacing material as well as with the same method using different technological parameters may exhibit different properties. This is due to differences in metallurgical reactions, cooling rates and the dilution [1,4-12].

Chromium cast irons are one of the most frequently used groups of alloys for hardfacing abrasion resistance layers. The surfacing material for applying this type of layers is mostly in the form of flux cored wire. Some flux cored wires are also intended for thermal spraying [6,13,14].

Available reference publications present results comparative tests of the abrasive wear resistance of coatings and layers made with selected surfacing materials using selected technologies.

In the work [15], abrasion resistance tests were carried out on arc-sprayed coatings with stainless steels (martensitic, austenitic, duplex), nickel alloy and composites (WC-Fe, WC-Co); HVOF-sprayed coatings with composites (WC-Ni, WC-Co); laser-surfaced WC-NiCr composite layer and submerged arc-surfaced Fe-Cr-C alloy layer. Studies [7,20] on the comparison of the properties of flame; arc; plasma; and HVOF-sprayed coatings with molybdenum wire revealed that the resistance to metal-mineral abrasion of individual coatings is different. Amushahi et al. [16] characterized an arc-sprayed and flux cored arc surfacing coating and layer with Fe-B alloy using metallographic microscopic examination, phase analysis and microhardness measurement. However, it was not possible to find quantitative data enabling the comparison of functional properties of coatings and layers made with different technologies using the same type of self-shielded flux cored wire having the structure of the chromium cast iron. In connection with the above, an attempt was made to determine the influence of the technologies of thermal spraying and surfacing by arc welding using flux cored wire on the abrasion resistance of the applied coating or layer.

The article presents results of tests concerning the metal-mineral abrasive wear resistance of arc-sprayed coatings at lower and higher air pressure (larger and smaller drops of metal) and HVOF-sprayed coatings deposited using the self-shielded flux cored wire providing the obtainment of the weld deposit of high-chromium cast iron Fe15 (in accordance with EN 14700). The significance of influence of the spraying technologies on abrasion resistance was determined using a completely randomized design. The scope of tests also included the analysis of the chemical and phase compositions as well as the microscopic metallographic tests of deposited (sprayed) coatings. For comparison, analogous tests were carried out for the overlay welds applied by self-shielded flux cored arc surfacing using the same flux cored wire.

2. TEST MATERIALS

The surfacing processes involved the use of a Hardface HC-O self-shielded flux cored wire (manufactured by Welding Alloys company) having a diameter of 2.8 mm, providing the obtainment of the weld deposit of high-chromium cast iron Fe15. Hardface HC-O wire is recommended for protecting surfaces exposed to intense metal-mineral abrasive wear and moderate impact loads. According to the manufacturer, the wire can also be used in thermal spraying. The chemical composition of the weld deposit of the surfacing material and the values of hardness after surfacing are presented in **Table 1** [14]. The thermally sprayed coatings were deposited on test plates (75 x 25 x 15 mm) made of structural steel S355N, while for flux cored arc surfacing with dimensions of 200 x 80 x 15 mm.

Table 1 Chemical composition of the weld deposit of the surfacing material and hardness after surfacing [14]

Chemical composition of weld deposit (wt%)					Hardness of the third layer of the overlay weld (HRC)
Fe	C	Cr	Si	Mn	
rest	5.0	27.0	1.5	1.5	58÷64

3. TESTS

3.1 Abrasive wear resistance tests

The tests aimed to identify the significance of a technology and parameters of thermal spraing with Hardface HC-O flux cored wire on the abrasive wear resistance of deposited coatings were performed using a completely randomised design making it possible to determine the significance of one input factor on an output factor [17]. The adopted effect significance level was $\alpha = 0.05$. It was assumed that the coatings would be made using two different technologies (arc spraying and HVOF). For arc-sprayed coatings, two levels of air flow are established. For each coating variant, 6 tests of metal-mineral abrasion resistance are planned. Following the previously adopted assumptions and the concept of randomisation, 18 lots of flux cored wire were designated with natural subsequent numerals from 1 to 18 (based on the date of manufacture, from the oldest to the latest). Afterwards, a computed random number generator was used to generate a sequence of random numbers [18]. The generated sequences of numbers were used to randomly assign the lots of the surfacing material given spraying technology. Before spraying, the specimens were subjected to dry abrasive grit blasting. The technological parameters used when making the coatings are presented in **Table 2**.

Table 2 Parameters used in the spraying of coatings

Thermal spraying techniques	Specimen designation	Process parameters				
		Current (A)	Arc voltage (V)	Air pressure (bar)	Spraying distance (mm)	
Arc spraying	A (lower air pressure)	150÷170	25.0	2.3	150	
	B (higher air pressure)			4.0		
HVOF	C	Oxygen flow rate (l/min)	Propane flow rate (l/min)	Air flow rate (l/min)	Wire feed rate (cm/min)	Spraying distance (mm)
		200	50	600	222	150

The tests concerning the resistance of the deposited coating to the metal-mineral type of abrasive wear were performed in accordance with the ASTM G 65 standard, procedure C. During the test, the abrasive flow rate was 389 g/min. The specimens were subjected to a constant force of 130 N. The rubber lined wheel rotated at a rate of 200 rpm, whereas the lineal abrasion amounted to 71.8 m. The abrasive material used in the tests was flame-dried quartz sand of spherically-shaped grains, characterized by granularity restricted within the range of 212÷300 µm. The surfaces of the coatings were not ground. The determination of the abrasive wear resistance of the sprayed coatings required the performance of the measurements of mass loss and coatings density. Before and after the test, the specimens were weighed using a laboratory balance, with an accuracy of up to 0.0001 g. The identification of the aforesaid density was based on three measurements of the density of the deposited coatings of one specimen weighed in air and in liquid. The volume loss was determined using the value of the mass loss of the specimen, the average value of the measured coating density and formula (1). The obtained results are presented in **Table 3**.

$$V_l = \frac{M_l}{\rho} \cdot 1000 \quad (1)$$

where:

- V_l - volume loss (mm^3)
- M^l - mass loss (g)
- ρ - density (g/cm^3)

Table 3 Results of tests concerning the metal-mineral abrasive wear resistance of the sprayed coatings

Specimen designation	Loss of coating volume (mm^3)* [loss of coating mass (g)]						
	1	2	3	4	5	6	Average value for individual levels
A	15.5833 [0.0974]	15.9032 [0.0994]	15.4873 [0.0968]	14.6393 [0.0915]	14.8633 [0.0929]	15.0713 [0.0942]	15.2580 [0.0952]
B	11.5988 [0.0769]	12.5339 [0.0831]	11.8250 [0.0784]	11.4178 [0.0757]	11.8250 [0.0784]	11.7496 [0.0779]	11.8250 [0.0784]
C	9.9271 [0.0703]	10.0825 [0.0714]	10.6191 [0.0752]	10.3225 [0.0731]	10.0119 [0.0709]	9.6447 [0.0683]	10.1013 [0.0715]
In relation to all results							12.3948 [0.0818]

* the loss of the volume of sprayed coatings was identified using formula (1).
The measured density of arc-sprayed coatings is 6.2503 g/cm^3 at lower air pressure, 6.6300 g/cm^3 at higher air pressure and HVOF 7.0816 g/cm^3.

The Table of the analysis of variance (**Table 4**) was made in accordance with the completely randomised design.

Table 4 Table of the analysis of variance

Source of variation	Sum of squares SS	Degrees of freedom DF	Mean square MS	Value of the test F
Between treatments	$SS_{Trt} = \sum_{i=1}^{K} r_i \bar{y}_i^2 - N\bar{y}^2 = 82.70133$	$DF_{Trt} = K - 1 = 2$	$MS_{Trt} = \frac{SS_{Trt}}{K-1} = 41.3507$	$F = \frac{SS_{Trt}}{SS_E} = 255.0938$
Error (within treatments)	$SS_E = \sum_{i=1}^{K}\sum_{j=1}^{r_i} y_{ij}^2 - \sum_{i=1}^{r_i} r_i \bar{y}_i^2 = 2.43075$	$DF_E = N - K = 15$	$MS_E = \frac{SS_E}{N-K} = 0.1621$	-
Total	$SS_T = \sum_{i=1}^{K}\sum_{j=1}^{r_i} y_{ij}^2 - N\bar{y}^2 = 85.13208$	$DF_T = N - 1 = 17$	-	-

where:
r_i - number of measurements of the input factor at a given level
N - total number of measurements of the input factor
$\bar{y}_i$- means of measurement results in the i-th line
$\bar{y}$ - mean of all measurements
y_{ij} - value of the j-th resultant factor at level i
K - number of variability levels of the test factor

In order to compare the abrasive wear resistance of the sprayed coatings, tests were carried out on six overlay welds layers using flux cored arc surfacing at Hardface HC-O self-shielded cored wire. The technological parameters used during the making of the hardfacing layers are presented in **Table 5**. Afterwards, each overlay weld was sampled for a specimen having dimensions of 75 mm x 25 mm. The location of cracks in the hardfacing layer was accidental. The cut-out specimens were subjected to girth abrasive grinding. The test results are presented in **Table 6**.

Table 5 Parameters used in the flux cored arc surfacing of layers

Welding current (A)	Arc voltage (V)	Polarity	Electrode feed rate (m/min)	Travel speed (cm/min)	Heat input* (kJ/mm)
~ 400	30.0	DCEP	4.3	60	0.960

* heat input calculated in accordance with EN 1011-1, for k = 0,8

Table 6 Results of the tests concerning the metal-mineral abrasive wear resistance of the overlay welds

Designation of overlay weld	Loss of overlay weld volume (mm^{3*}) [loss of overlay weld mass (g)]	Mean loss of overlay weld volume (mm^{3*}) [mean loss of overlay weld mass (g)]
D1	3.3656 [0.0249]	3.3025 [0.0244]
D2	3.5278 [0.0261]	
D3	3.1223 [0.0231]	
D4	2.9331 [0.0217]	
D5	3.2034 [0.0237]	
D6	3.6630 [0.0271]	

* the loss of the volume of overlay welds was identified using formula (1).
The measured density of the overlay weld amounted to 7.3984 g/cm^3

3.2 Chemical composition analysis

The analysis of the chemical composition was performed using optical spark emission spectrometry. Each specimen's surface was subjected to three chemical composition analyses. The mean values of the contents of chemical elements are presented in **Table 7**.

Table 7 Results of the analysis of the chemical composition of the sprayed coatings and the overlay weld

Specimen designation	Surfacing process	Chemical composition (wt%)								
		Fe	C	Cr	Si	Mn	Ni	Mo	Nb	B
A1	Arc spraying (lower air pressure)	rest	5.10	26.01	1.69	1.28	0.09	0.05	0.01	0.49
B1	Arc spraying (higher air pressure)	rest	5.03	26.06	1.76	1.25	0.09	0.05	0.01	0.51
C1	HVOF	rest	4.90	24.83	1.29	1.54	0.06	0.05	0.01	0.16
D1	Flux cored arc surfacing	rest	3.26	23.39	1.23	1.19	0.11	0.04	0.01	0.14

The mean value (calculated using formula (2) [19]) of the proportion of carbon and chromium ratio in the deposited coatings and the layer to the contents of the same chemical elements in the all-weld metal deposit of a given surfacing material amounted to 0.99 in relation to the arc-spraying at lower and higher air pressure as regards the HVOF-spraying 0.95 and 0.76 in terms of to the flux cored arc surfacing.

$$y_{zp} = \frac{\left(\frac{C_{cc}}{C_{csm}} + \frac{Cr_{cc}}{Cr_{csm}}\right)}{2} \qquad (2)$$

where:

y_{pche} - mean of the proportion of the content of carbon and chromium

C_{cc} - content of carbon in the coating (layer) (wt%)

C_{csm} - content of carbon in the all-weld metal deposit of the surfacing material (wt%)

Cr_{cc} - content of chromium in the coating (layer) (wt%)

Cr_{csm} - content of chromium in the all-weld metal of the surfacing material (wt%)

3.3 Phase composition analysis

The analysis of the phase composition of the thermal spraying coatings and hardfacing layer involved the use of an X'Pert PRO diffractometer (PANalytical) and the filtered (filter Fe) radiation of a cobalt X-ray tube. The measurements were performed within the range of 30° to 130° of angle 2θ with an increment of 0.026° 2θ and a counting time of 40 s. The phase identification was based on the database of International Centre for Diffraction Data PDF-4+ (year 2020). The phase identification results are presented in **Figure 1**.

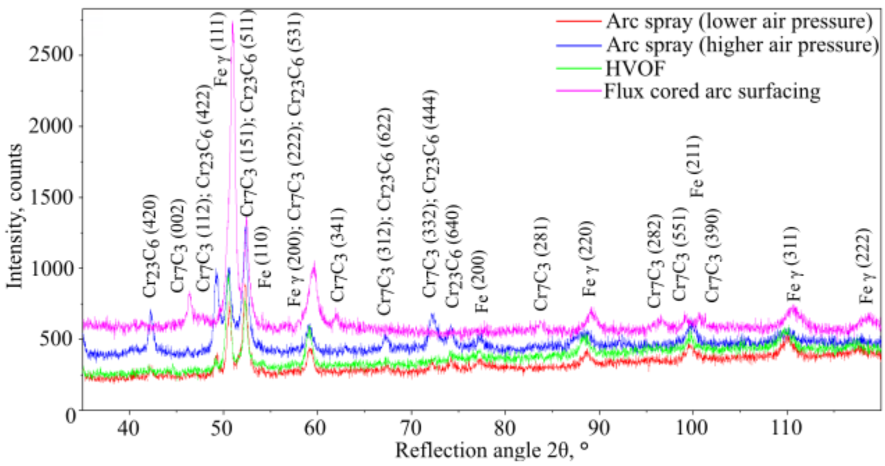

Figure 1 XRD pattern of the thermal spraying coatings and hardfacing layer

3.4 Microscopic metallographic tests

The identification of the quality of the coatings and layers required the performance of microscopic metallographic tests. The metallographic tests of selected coatings and layer involved the use of a light microscope and cross-sectional metallographic specimens. The results of the metallographic test results are presented in **Figures 2a; 2b, 2c, 2d**.

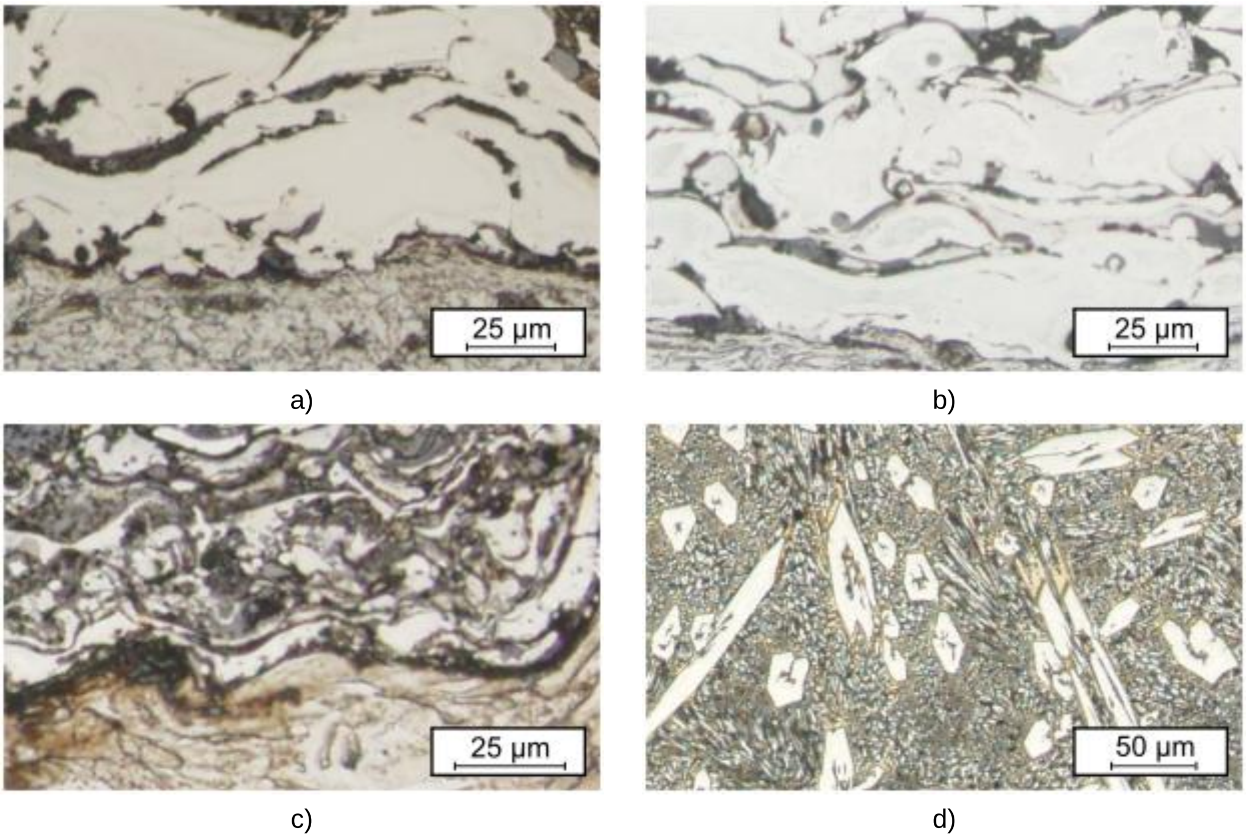

Figure 2 Microstructure of: a) arc-sprayed coating at lower air pressure; b) arc-sprayed coating at higher air pressure; c) HVOF-sprayed coating; d) flux cored arc surfacing layer

4. ANALYSIS OF TEST RESULTS

The tests concerning the abrasive wear resistance of the thermal sprayed coatings made using self-shielded flux-cored wire (Hardface HC-O) revealed that the coatings were characterised by high abrasion resistance regardless of the applied thermal spray technology as technological conditions (air pressure). The mean loss of the volume of the coating determined on the ASTM G 65 standard amounted to 15.2580 mm^3 in relation to the arc-sprayed coatings at lower air pressure, 11.8250 mm^3 in relation to the arc-sprayed coatings at higher air pressure and 10.1013 mm^3 in relation to the HVOF-sprayed coatings. Regardless of the thermal spray process, the coatings provided the metal-mineral abrasive wear resistance lower than that of the overlay welds made by self-shielded flux cored arc surfacing. This may be influenced by unequal preparation of the surface of the specimens to be tested [1]. In the case of sprayed coatings, they were not ground. Most likely, the occurring surface irregularities contributed to the intensification of the abrasive wear process, especially in its initial phase. The tests concerning the significance of the effect of a given thermal spray process on the abrasive wear resistance of the deposited coatings was performed using the completely randomised design. The value of test F, calculated on the basis of the statistical analysis of the test results (Table 4), was lower than critical value $F_{0.05;\,2;\,15}$ of the Fischer-Snedecor F test [17]. The foregoing justified the conclusion that, in relation to the adopted level of significance and the calculated numbers of the degrees of freedom, the thermal spray process significantly affect the metal-mineral abrasive wear resistance of applied coatings using flux cored wire, which has the structure of the high-alloy chromium cast iron. Regardless of the surfacing process, all of the coatings and layers provided the chemical composition of alloy Fe15.

The mean of the proportion of carbon and chromium ratio in the deposited coatings and the layer to the contents of the same chemical elements in the all-weld metal deposit of a given surfacing material amounted to 0.99 in relation to the arc-spraying at lower and higher air pressure as regards the HVOF-spraying 0.95 and 0.76 in terms of to the flux cored arc surfacing. The difference between coatings and layers results from the melting of the base material surface in the flux cored arc surfacing. While, differences in the chemical composition between different variants of the sprayed coatings and the hardfacing layer result from the losses of alloying elements during the deposition process and are an individual characteristic of each process.

The metallographic tests did not reveal the presence of imperfections in any of the coatings and layer subjected to analysis.

The chemical composition analysis, the analysis of phase composition as well as the microscopic tests revealed that structure of all thermal sprayed coatings have a lamellar splat structure characteristic of the thermal spray process, in which phases such as Cr_7C_3, $Cr_{23}C_6$, austenite and ferrite are present. For arc-sprayed coatings, much larger metal droplets forming the coating can be observed at lower air pressure. The HVOF-sprayed coatings were made from the smallest particles and oxides arranged parallel to the substrate surface. The above structure may provide greater wear resistance [9]. The structure of the overlay weld was composed of Cr_7C_3 carbides in the matrix consisting of austenite with a slight amount of ferrite.

5. CONCLUSION

Based on the conducted tests of the properties of arc-sprayed coatings (at lower and higher air pressure), HVOF-sprayed coatings and flux cored arc surfacing using self-shielded cored wire ensuring the weld deposit of high-alloy chromium cast iron, the following conclusions can be formulated:

1) In relation to the adopted level of significance and the calculated numbers of the degrees of freedom, the thermal spray technologies subjected to analysis significantly affect the metal-mineral abrasive wear resistance of the deposited coatings using flux cored wire having the structure of the chromium cast iron.
2) The applied surfacing technologies enabled the obtainment of the coatings and layer free from imperfections. In all of the variants the structure of coatings was composed of phases such as Cr_7C_3, $Cr_{23}C_6$, austenite and ferrite. The structure of the overlay weld was composed of Cr_7C_3 carbides in the matrix consisting of austenite with a slight amount of ferrite.

ACKNOWLEDGEMENTS

The results of the contribution were achieved by solving the specific research project No. SP2023/020 with the name "Research and Optimisation of Engineering Technologies" solved in 2023 at the Faculty of Mechanical Engineering of VSB - Technical University of Ostrava.

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