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The properties of thermal sprayed aluminium coatings on non-alloy structural steel

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ABSTRACT

Purpose: of this paper was comparison of the structure, hardness and erosive wear of aluminium coatings produced on non-alloy structural steel S355JR (EN 10025-2) using the powder flame spraying and wire arc spraying methods.

Design/methodology/approach: The latest model of flame powder sprayer and wire arc sprayer was used in the experiments. This provided very reliable spraying conditions. The additional material for flame-spraying was of Metco 54NS-1 pure aluminium powder (EN AW 1100 series). In the arc spraying process the Metco Aluminium (EN AW 1100 series) 1.6 mm diameter pure aluminium thermal spray wire was used. In each spraying technology binding alloy, i.e. Ni-Al, was employed as a primer coating. The used spray processes produced dense, abrasion and erosion resistant coatings approximal 1.0 mm thick. Aluminium coatings were characterized in accordance with ASTM G 76-95 erosion resistance tests, ASTM C 633-01 adhesion strength, HV 0.1 hardness tests and metallographic analyses. The scope of research included: preparation material for spraying, selection of properly process parameters for each sprayed technique based on preliminary technological tests, coatings manufacturing, examining the structure and tribological properties of aluminium coatings, comparison of obtained samples.

Findings: The obtained results have proven superior properties of arc sprayed aluminium material coatings and have shown to be promising in industrial applications.

Research limitations/implications: The presented test results are a preliminary assessment of the properties of thermally sprayed aluminium coatings. Therefore, further research is required regarding the resistance of aluminium coatings to abrasion and corrosion.

Practical implications: The study is focused on selecting the best and most economical technique for manufacturing of wear and corrosion resistance aluminium coatings with a thickness of approximately 1 mm.

Originality/value: It has been demonstrated that the use of a Ni-Al primer coating improves the adhesion of flame and arc sprayed aluminium coatings to steel surfaces.

Keywords: Flame powder spraying, Wire arc spraying, Non-alloy structural steel, Erosion wear resistance, Adhesion strength, Impact wear

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PROPERTIES

1. Introduction

Methods of thermal spraying have undergone many changes and developments in recent years; thanks in part to advances made in heat source technology and newly developed coating materials [1-5]. Currently around 70% of industrial applications involving thermal spraying are used to produce new machinery parts or devices, which require a high finish and surface finish quality. The use of thermally sprayed coating has not only increased the longevity protection features of steel assemblies against the effects of environmentally induced corrosion but has also contributed to prolonging the service time of parts used in textile machinery, pump and mixer components, plastic injection moulding machines and improved the reliability and durability of boiler. Aluminium coating are applied to structural components and devices made of steel, cast steel or cast iron which are exposed to potentially corrosive environments in water, atmospheres including exhaust gases regularly at 900°C and periodically up to 1100°C. Steel alloys coated by this method show an increased temperature and hostile environment resistance, especially in respect to sulfur [6-11]. Aluminium coatings are most commonly used in constructions with corrosivity categories of C4 and higher (ISO 12944-2:2001) and at pH 4 to 8.

2. Materials and the methodology

Spraying tests were carried out at the production stations. Aluminium coatings tests were performed on certified laboratory devices.

2.1. Research objectives and spraying parameters

The chemical composition of the steel substrate – the non-alloy structural steel S355JR certified according to EN 10025-2 [12] is given in Table 1.

Table 1.
Chemical composition of the no-alloy structural steel S355JR (according to EN 10025-2:2019)

C	Mn	Si	P	S	N	Fe
0.24	1.6	0.55	0.045	0.045	0.009	Bal.

Binding powder Metco 450NS, Table 2, i.e. Ni-Al alloy, was employed as a primer coating. The additional material for flame-spraying was used of aluminium powder (EN AW 1100 series), Table 3.

Table 2.
Chemical composition of the binding nickel base powder Metco 450NS

Al	Ni	Nominal particle size distribution, µm
5	Bal.	-106 + 45

Table 3.
Chemical composition of Metco 54NS-1 pure aluminium powder (EN AW 1100 series)

Al, min	Nominal particle size distribution, µm
99 +	–75 + 45

The spraying process was carried out in accordance with the standard EN 13507:2010 [13] on workstation, equipped with RotoTec 80 manuals torch and hand-guided modern oxy-acetylene system – CastoDyn DS 8000, Figure 1.

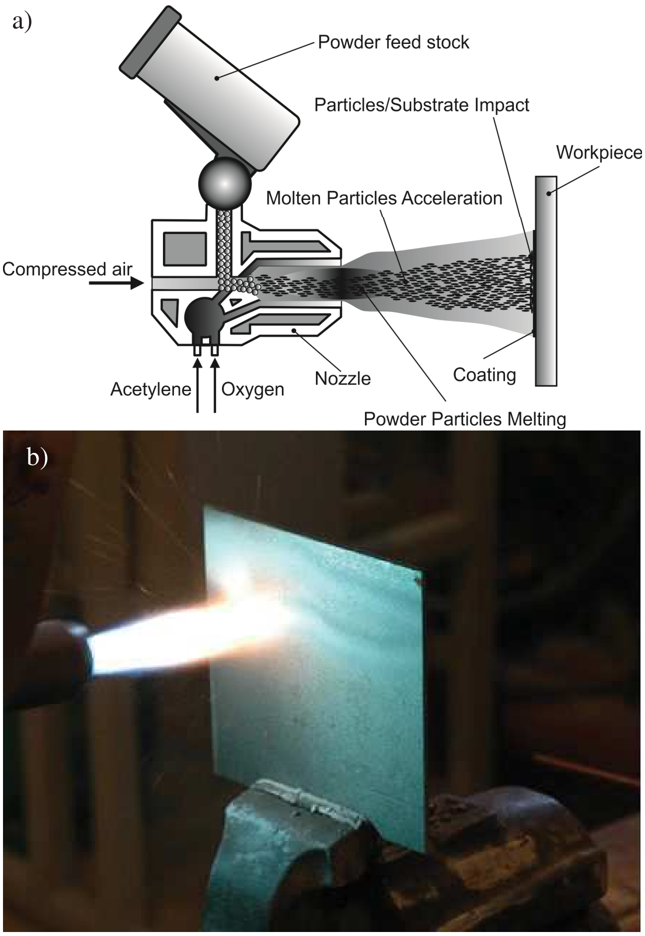


Fig. 1. Flame spraying process: a) a diagram of handheld flame jet burner; b) a photo from trials of flame-spraying aluminium coatings with CastoDyn DS 8000 burner

Plates with dimensions of 150x150x5 mm were subjected to sand-blasting process and preheated with a gas burner up to a temperature of 40°C before the spraying process (the temperature of preheating was measured using pyrometer).

The flame jet burner was guided in a horizontal position covering the whole surface of the sheet. During the process the spraying direction was changed several times by 90°, until obtained thickness of coating was about 1.0 mm.

The spraying process consisted of the following operations:

- a 50 to 100 µm thick primer coating was sprayed with Ni-Al-Mo powder with a RotoTec 80 torch, Table 4;
- an approx. 900 µm thick external specific coating was sprayed with aluminum EN AW 1100 series powder using a CastoDyn DS 8000 torch, Table 5.

Table 4.
Spraying properties of primer coating with Ni-Al powder (Metco 450NS)

Torch type	RotoTec 80
Acetylene pressure	0.7 bar
Oxygen pressure	4.0 bar
Distance between torch and sprayed surface	200 mm
Preheating temperature	40°C
Change of torch advancement angle relative to the next coating	90°

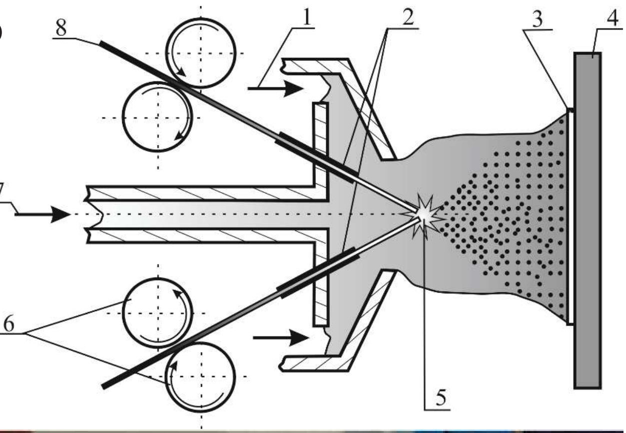
Table 5.
Spraying parameters of external coating with Metco 54NS-1 pure aluminium powder (EN AW 1100 series)

Torch type	CastoDyn DS 8000
Torch tip	SSM 30
Powder flow rate	2 (setting acc. to manual)
Acetylene pressure	0.7 bar
Oxygen pressure	4.0 bar
Assist gas (air) pressure	3.0 bar
Notes: The required primer coating made with Ni-Al powder	

The arc spraying process was carried out in an upright position with a EuTronic Arc Spray 4 power source and a Gun 4 manual spray gun, Figure 2.

During arc spraying, two types of the Metco 8400 solid wires were used; for the 100 µm thick buffered subcoating, a nickel-aluminium with a diameter of 1.6 mm (AWS C2.25/C2.25M), Table 6 and, for the outer coating a 900 µm thick Metco Aluminium (EN AW 1100 series) solid wire with a diameter of 1.6 mm (AWS C2.25/C2.25M), Table 7. Arc spraying samples were prepared in accordance with ISO 14923:2005 [8]. Optimal processing parameters are shown in Table 8.

a)



b)

Fig. 2. Arc spraying process: a) a scheme of wire arc spraying apparatus: 1 – compressed air; 2 – wire electric contact; 3 – sprayed layer; 4 – base metal; 5 – electric arc; 6 – wire feeder; 7 – compressed air, 8 – welding wire; b) a photo from trials of arc spraying aluminum coatings with EuTronic Arc Spray 4 equipped with a Gun 4 spray gun

Table 6.
Chemical composition of the Metco 8400 solid wire (according to AWS C2.25/C2.25M)

Al	Ni
5	Bal.

Table 7.
Chemical composition of the Metco Aluminium (EN AW 1100 series) solid wire (according to C2.25/C2.25M)

Al (min)	Cu (max)
99 +	0.05-0.2

Table 8.
Arc spraying parameters for buffered subcoating and aluminium outer coating applied to no-alloy structural steel S355JR

Nozzle distance from material, mm	150-200
Current, A	120
Arc Voltage, V	34
Spray gas pressure, bar	4.2

Note: Ni-Al buffered dub coating (Metco 8400) and aluminum outer coating (Metco Aluminium) were both applied with identical parameters.

2.2. Analysis of coating erosion resistance

The erosion resistance of aluminium arc sprayed coating were tested in accordance with ASTM G76-95 [14] as shown in Figure 3. Alumina (Al_2O_3) powder was used as the erosive material with a particle diameter of 71 µm . The erodent particle velocity was 70 ± 2 m/s, with efficiency of the erodent application set at 2.0 ± 0.5 g/min with a nozzle outlet distance from the test surface set 10 mm. Erosion resistance tests were performed at 90° and 30° [15,16].

2.3. Metallographic analysis of coatings

Microscopic and macroscopic studies were carried out in the cross-sectional plane and on the surface of samples (sample without buffered subfloor and with nickel-aluminium buffered subcoating). Microscopic and macroscopic studies were conducted on the Olympus GX 71 light microscope. Surface analyses were carried out on an LEO 435 VP electron scanning microscope.

2.4. Coating hardness measurements

The hardness test of the aluminium shell and arc sub-cushion was done using Vickers HV0.1 (Aluminium and Nickel Alloy Buffer Substrate) and HV1 (Substrate – no-alloy structural steel S355JR) on a Micro-Hardness Tester 401MVD ™. The test was carried out in accordance with ISO 6507-1.

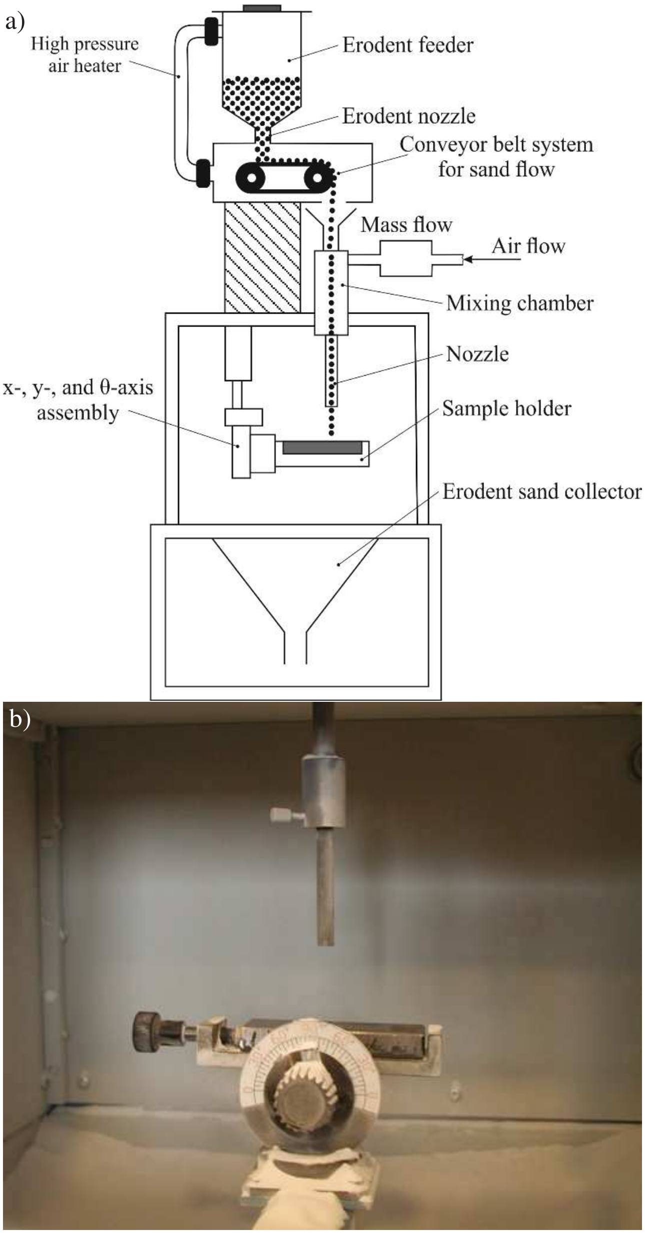


Fig. 3. Erosion resistance test rig according to ASTM G 76-2: a) a schematic view, b) the interior view of the erosion measuring chamber

2.5. Analysis of coating adhesion strength

An attempt to determine the adhesion of the aluminium coating arc-sprayed to the steel substrate was carried out in accordance with ASTM C 633-01. For no-alloy structural steel S355JR steel plates subjected to arc sprayed aluminium without buffering subcoat and with nickel-aluminium buffered subcoating, 40 mm diameter discs were cut. The sprayed samples were glued together against the samples using Henkel Loctite® Hysol® 3478 A & B Superior Metal Adhesive. Static testing was performed on a Zwick device.

2.6. Analysis of coating shock resistance

The impact resistance testing of aluminium arc-coated castings on a steel substrate were carried out on a specially constructed test stand, patented PL 200880, Figure 4.

The spray coating resistance criteria was the number of cracks and shattered shell fragments produced by repeated impact on the sprayed surface, 20.0 kg carbon steel spatula tool, freely released from the height of 1.02 m (impact energy 200 J), the surface quality of the sprayed coating was evaluated on the basis of visual analysis at 50, 100, 150 and 200 strokes.

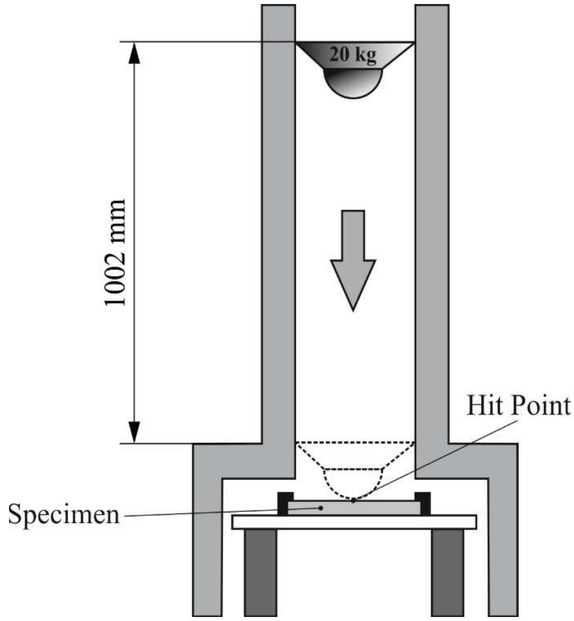


Fig. 4. Stand for impact resistance tests on impact coatings. Reserved by Patent PL 200880

Erodent strike angle, °

Sample PE 1

Sample PE 2

90

30

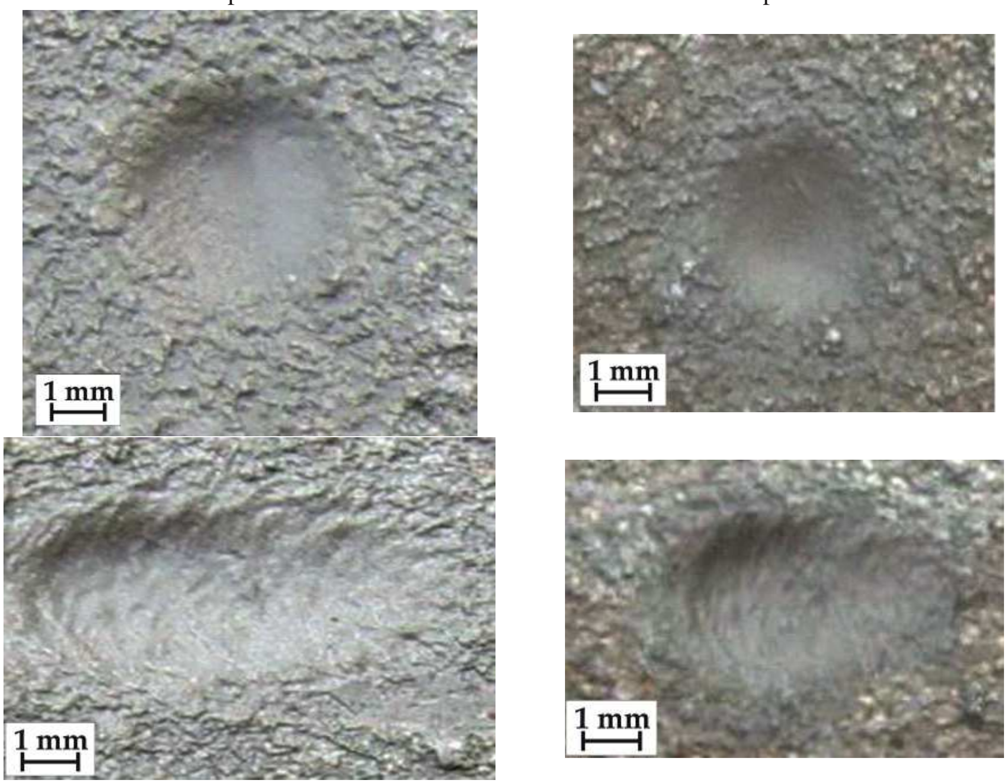


Fig. 5. PE 1 and PE 2 samples after erosion test, comparison of erodent effect on the sample surfaces for each of the angles studied

3. Results and discussion

3.1. Coating erosion resistance result

The relative erosive wear resistance test results of the flame-sprayed aluminium coating (PE1) and of the arc-sprayed aluminium coating (PE2), are presented in the Table 9 and in the Figure 5.

3.2. Metallographic test results of coatings

The images of the cross-sectional coatings of the samples are shown in Figure 6.

Table 9.
Summary of results obtained during the erosion wear test ASTM G76-95

Erodent strike angle, °	Sample no.	Mass loss [1)], g	Volume loss, mm^3	Erosion rate, g/min	Resistance to erosion as per ASTM G76, $0.001mm^3/g$
90	Sample PE1	0.0054	1.985	0.00068	0.12255
	Sample PE2	0.0036	1.324	0.00045	0.08170
30	Sample PEl	0.0052	1.417	0.00082	0.06998
	Sample PE2	0.0026	0.836	0.00042	0.04250

Notes: [1)] – average weight loss determined on the basis of three tests; erosion rate [g/min] = mass loss of sample [g]: exposure time [min]; Erosive wear resistance [$0.001mm^3$ / g] = volume loss of the sample [mm^3]: total mass of the erodent used in the test [g]; Density of aluminium spray coating 2.72 [g / cm^3], mass of erodent used 16.2 [g], test time 8 [min].

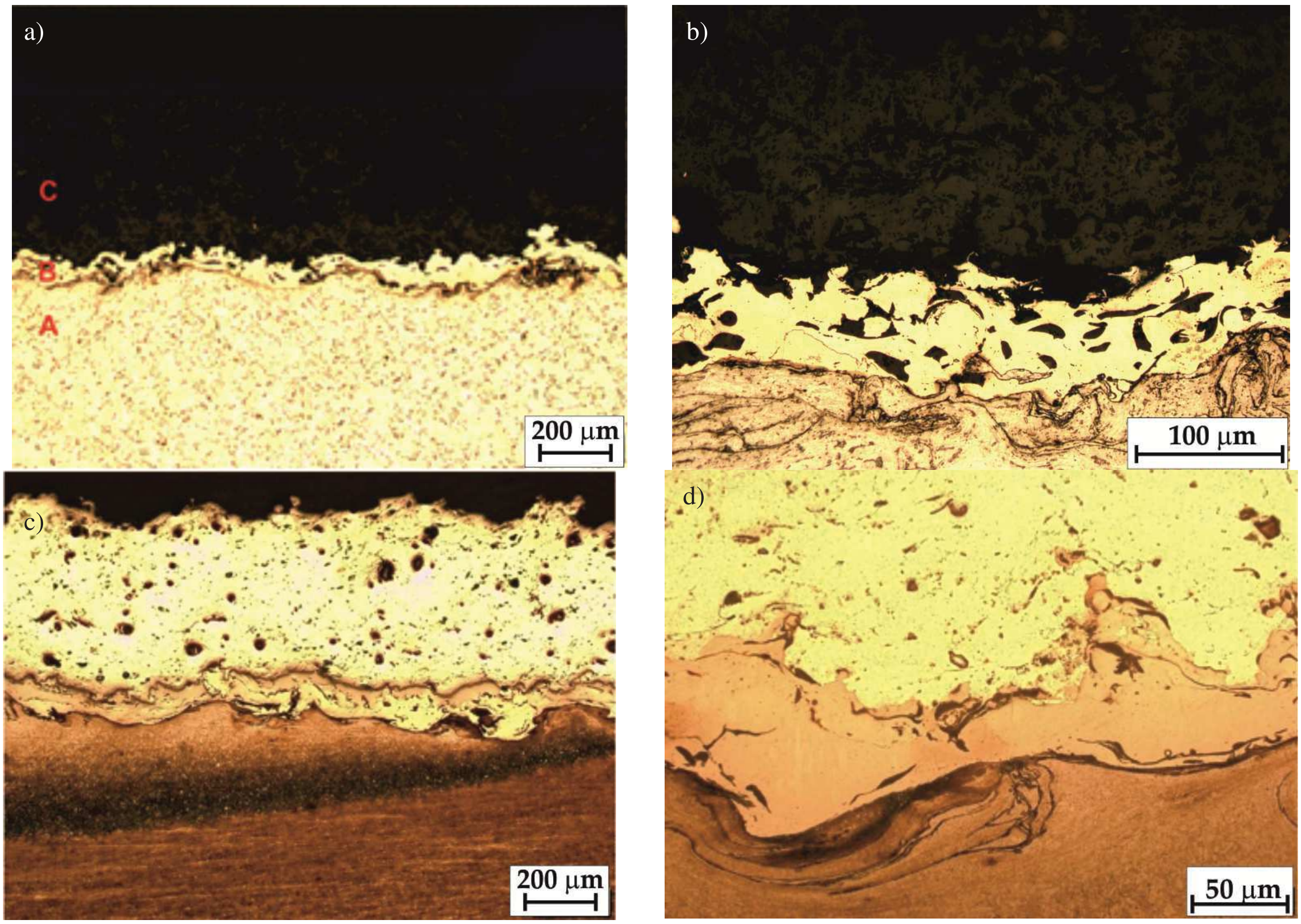


Fig. 6. The macro and microstructure of the thermal sprayed pure aluminium coatings: a) structure of specific external coating (C), primer Ni-Al coating (B) and base material (A): a), b) images of the flame-sprayed coating, mag. x200 and x100; c), d) images of the arc-sprayed coating, mag. x200 and x500

3.3. Coating hardness testing results

Hardness measurements were made on the cross-section of sprayed coatings according to the scheme showed in the Figure 7. Results of hardness measurements measured on cross-section of thermal sprayed aluminium castings on non-alloy structural S355JR steel are shown in Table 10.

3.4. Coating – subcoating adhesion results

The results of adhesion testing of the flame-sprayed (PE1) and of the arc-sprayed (PE2) aluminium coatings with nickel-aluminium buffered subcoating are presented in Table 11.

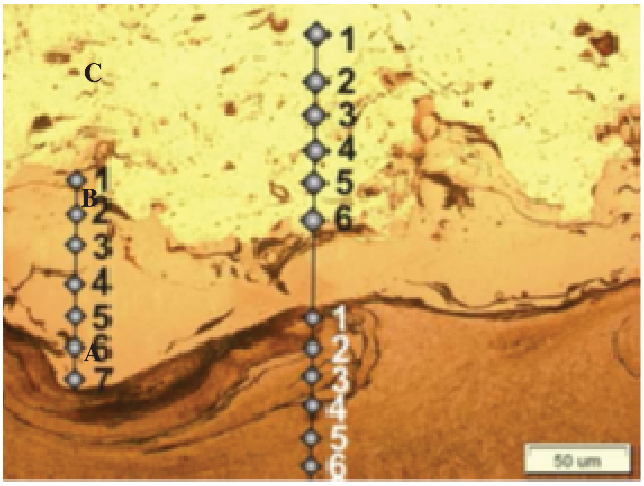


Fig. 7. The scheme of hardness measurements on thermal sprayed aluminium coatings

Table 10.
Results of hardness measurements measured on cross-section of thermal sprayed aluminium castings on non-alloy structural S355JR steel

Sprayed coating hardness		
Measurement number	Sample PE 1	Sample PE 2
	Aluminium coating [HV0.3]	
1	38.8	38.9
2	35.8	39.8
3	41.9	43.4
4	36.0	46.9
5	35.3	48.2
6	36.8	52.1
Average aluminium coating hardness	37.4	44.9
Buffered Ni-Al subcoating [HV0.3]		
1	140.7	138.2
2	131.5	140.6
3	138.1	153.6
4	131.6	145.2
5	139.1	136.5
6	138.7	138.4
7	138.3	145.1
Average subcoating hardness	136.9	142.5
Average hardness of six measurements in the HAZ of S355JR steel	254.1	242.4

Table 11.
Summary of results obtained during the static tensile test of thermal sprayed aluminium coatings

Results of static tensile testing					
Sample	Sample number	Max Tensile force, kN	Surface area, mm^2	Sprayed coating adhesion, N/mm^2	Average coating adhesion, N/mm^2
PE 1	1	14.8	1256.6	11.8	12.6
	2	16.2		12.9	
	3	16.2		12.9	
PE 2	1	21.3		17.0	16.0
	2	19.6		16.0	
	3	19.1		15.2	

3.5. Coating shock load testing results

The results of resistance tests of the flame-sprayed (PE1) and of the arc-sprayed (PE2) aluminium coatings on impact loads are shown in Figure 8.

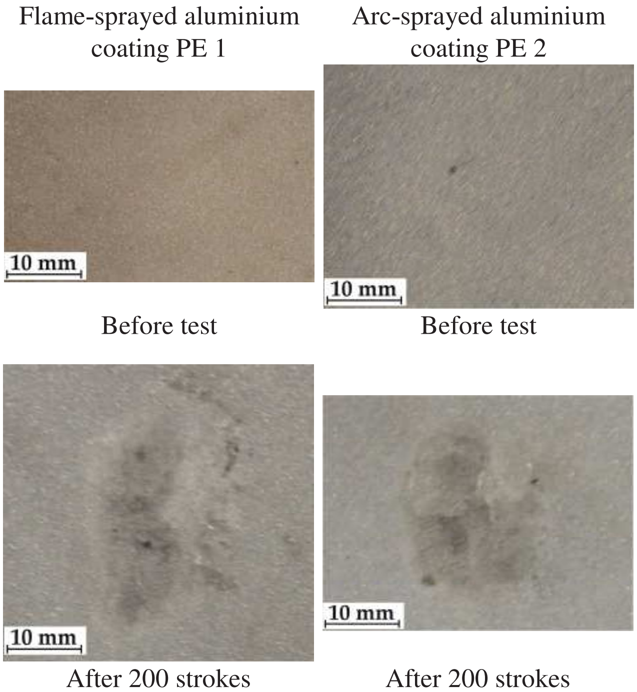


Fig. 8. View of thermal sprayed aluminium coatings on non-alloy structural S355JR steel after impact resistance tests (impact energy 200 J)

3.6. Discussion

After carrying out a spraying process, the visual examinations made did not reveal any sample surface nonconformities after flame spraying with Metco 54NS-1 powder and Metco Aluminium (EN AW 1100 series) wire. The metallographic examinations of the microsections perpendicular to the surface of the sample flame-sprayed with Metco 54NS-1 powder have shown that two coatings existed, respectively, on the surface of steel with developed surface line: a primer coating (B) and external specific coating (C), (Fig. 6a) A 40 µm to 110 µm thick primer coating (B) consisting of bright areas made of Ni-Al alloy and dark oxide inclusions, (Fig. 6b), was observed immediately above the base material surface (A). A banded structure in the base material, distinctive for the strengthening of the steel surface during shot blasting of the examined material, existed in the boundary area with a primer coating. An external coating, formed in the spraying process, with its thickness varying between 850 µm to 910 µm, existed in the primer coating. The coating possessed numerous voids with different size and a waved line of its external surface.

A primer coating (B) and an external specific coating (C) existed on the steel surface with a developed surface line after arc-spraying with Metco Aluminium (EN AW 1100 series) wire, (Fig. 6c). A banded structure with a considerable plastic deformation, existing on the thickness of approx. 50 µm, was observed underneath the primer coating in the steel. The primer coating consisted of bright areas of elements forming part of the Ni-Al powder used for spraying, and also of dark flattened oxides, (Fig. 6c). The coating was 50 µm to 160 µm thick. About a 900 µm thick external specific coating possessed few voids with a developed line of its external surface, (Fig. 6d).

It was confirmed, based on erosion resistance tests, that a coating arc-sprayed with Metco Aluminium (EN AW 1100 series) wire possesses higher erosion resistance (determined by mass loss) than a coating flame-sprayed with Metco 54NS-1 powder. In case of erosion tests at the angle of 90° and 30°, a mass loss of a sample coating arc-sprayed with with a Metco Aluminium (EN AW 1100 series) wire was, respectively, 0.0036 g and 0.0026 g, while of a sample coating flame-sprayed with a Metco 54NS-1 powder was about 50% higher, (Tab. 9).

Hardness measurements were carried out on the microsections of samples from of a flame sprayed coating with Metco 54NS-1 powder and Metco Aluminium (EN AW 1100 series) wire in microareas of the external coating (C), primer coating (B) and the steel substrate (A), (Fig. 7). The external coating flame-sprayed with Metco 54NS-1 powder had the average hardness of 37.4 HV0.3. The hardness of the examined microareas in the primer coating was higher, i.e. 136.9 HV0.3. Hardness in the boundary zone with the primer coating in the substrate material was approx. 244.1 HV0.3, as confirmed by the occurrence of a narrow heat-affected zone (HAZ) or by steel surface strengthening after shot blasting. The hardness of steel within approx. 500 µm from steel was ca. 220 HV0.3 and was characteristic for a ferritic structure with a small amount of cementite and perlite. The hardness of the external specific coating after an arc spraying operation with Metco Aluminium (EN AW 1100 series) wire was higher i.e. 44.9 HV0.3. The hardness of the primer coating was from approx. 143 HV0.3. A deformed area of steel with a banded structure in the boundary zone with the primer coating exhibited the maximum hardness of 242.4 HV0.3.

The substrate adherence of thermal sprayed aluminium coatings determined with a static stretching test until detaching a coating from the substrate has exhibited that the adherence of a coating arc-sprayed with Metco Aluminium (EN AW 1100 series) wire was higher than of a coating flame-sprayed made with Metco 54NS-1 powder and was, respectively, 16.0 MPa, and 12.6 MPa, (Table 11). The difference between tensile strength and adhesion values was confirmed by inhomogeneous microsections of the samples' surface after a tensile test.

The results of resistance tests on impact loads (impact energy 200 J), of the flame-sprayed (PE1) and of the arc-sprayed (PE2) aluminium coatings no shown damages in the form cracks and delamination, (Fig. 8).

4. Conclusions

Analysis of the results of the investigations into the development of technological conditions of aluminium coatings thermal spraying with a thickness of about 1.0 mm, with a buffered alumina a primer coating sprayed with solid wire and powder on the no-alloy structural steel S355 JR, allows has shown:

1. Flame spraying with Metco 54NS-1 powder and arc spraying with Metco Aluminium (EN AW 1100 series) wire out within the range of the selected parameters allowed to achieve high quality aluminium coatings approx. 1,0 mm thick on a steel substrate.
2. The coating arc-sprayed with Metco Aluminium (EN AW 1100 series) wire possesses higher erosion resistance (determined by mass loss) than a coating flame-sprayed with Metco 54NS-1 powder.
3. The use of nickel alloy buffer (95%Ni-5%Al) increases the adhesion of the aluminium coating onto the no-alloy structural steel S355 JR steel substrate.
4. Metallographic studies of thermal sprayed aluminium coatings showed the adhesion-mechanical nature of the joint between coating and the no-alloy structural steel S355 JR steel substrate.
5. The external flame sprayed and arc-sprayed aluminium coatings on sub-casing of nickel alumina was a mean hardness of 37.4 HV0.3 and 44.9 HV0.3 respectively. The mean hardness of the buffered nickel alumina coating was approx. 140 HV0.3.

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