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Comparison of the Structure and Mechanical Properties of Coatings Arc-Sprayed with Eutronic Arc Flux-Cored Wires

Porównanie struktury i właściwości mechanicznych powłok natryskiwanych łukowo drutami proszkowymi typu Eutronic Arc

Abstract: The article compares the erosion resistance, roughness and hardness of coatings produced by arc spraying. The study was conducted to compare the properties of arc-sprayed coatings with EuTronic Arc 599 and EuTronic Arc 595 powder wires on ASTM A516 Gr. 55 unalloyed steel substrates. Tests showed that the EuTronic Arc coatings exhibited very high hardness, averaging 755 HV for the EuTronic Arc 595 coating and 821 HV for the Eutronic Arc 599 coating. Application of the coatings increased the hardness, relative to the parent material, by 360 % and 400 %, respectively. The EuTronic Arc 599 coating showed a significantly higher roughness averaging 16.12 μm, compared to 12.35 μm for the EuTronic Arc 595 coating, which was likely caused by greater plasticization of the material during spraying resulting from the absence of carbides.

Key words: spraying, coating, arc spraying, erosion resistance

Streszczenie: Artykuł zawiera porównanie odporności erozyjnej, chropowatości oraz twardości powłok wytwarzanych metodą natryskiwania łukowego. Przeprowadzone badania miały na celu porównanie właściwości powłok natryskiwanych łukowo drutami proszkowymi EuTronic Arc 599 oraz EuTronic Arc 595 na podłoże ze stali niestopowej ASTM A516 Gr. 55. Badania potwierdziły, że powłoki EuTronic Arc wykazują bardzo wysoką twardość, wynoszącą średnio 755 HV dla powłoki EuTronic Arc 595 oraz 821 HV dla powłoki Eutronic Arc 599. Naniesienie powłok podwyższyło twardość, w stosunku do materiału rodzimego, odpowiednio o 360 % oraz 400 %. Powłoka EuTronic Arc 599 wykazała znacznie wyższą chropowatość, wynoszącą średnio 16,12 μm, w stosunku do 12,35 μm dla powłoki EuTronic Arc 595, co prawdopodobnie zostało spowodowane większym uplastycznieniem materiału podczas natryskiwania, wynikającym z braku obecności węglików.

Słowa kluczowe: natryskiwanie, powłoka, natryskiwanie łukowe, odporność erozyjna

1. Introduction

The durability of machines and equipment is limited by the wear and tear of their components. Because individual machinery parts are subjected to various stresses, they are made of different materials, providing the former with the highest possible durability in relation to the price of manufacture. The advanced development of science, manufacturing techniques and pursuit of the minimisation of production costs entail increasingly high demands for materials restrictions related to the weight of components. Solutions to the above-named problems are provided by cutting-edge surface engineering methods. Because most damage is initiated on the surface of components, various methods used to refine the surface of parts include, among other things, thermo-chemical treatment and the application of various surface layers made using welding techniques. It is also possible to observe a growing interest in materials of non-homogeneous structure, where properties required to perform difficult operation-related tasks are obtained by adjusting the composition of the surface layer. In such a way, it is possible to obtain a product containing 90 % of a cheaper classic structural material and covered with the surface layer characterised by improved properties.

In industry, corrosion-resistant coatings have been deposited for many years by means of spraying techniques. The launch of plasma torches enabled the application of not only metallic but also ceramic coatings. Improvements in the design of gas and arc spray torches and the invention of new spray materials have made the above-named methods complementary to plasma spraying. In addition, the improved quality of sprayed surfaces enabled their use in situations previously restricted to surfacing.

Table 1 presents examples of compounds used in relation to various types of wear.

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Table 1. Groups of materials used in relation to various types of wear

Type of wear	Thermal spraying methods	Sprayed materials
Atmospheric corrosion	Flame	Druty z Zn, stopy Zn-Al, Al, Al-Mg Al_2O_3, Al_2O_3-TiO_2, CrO_2 powders
	Arc	All the above-named materials + stainless steels, NiCr-based alloys
High-temperature corrosion	Flame	Al wires, alloys with high chromium contents in nickel or iron matrixes ZrO_2, $ZrO_2+Y_2O_2$ and other powders
	Plasma	ZrO_2, $ZrO_2+Y_2O_2$ powders and other materials with improved thermal properties
	Arc	Al, alloys with high Cr contents on nickel or iron matrixes
Abrasive wear	Flame	Self-fluxing type powders with melting
	Arc	Fe or Ni-based wires modified with phases of carbides, borides, silicides, etc.
	HVOF	Composite powders: WC-Co, WC-Co-Cr, NiCr-CrC, WC and CrC-Ni
Abrasive and corrosive wear at elevated temperatures	Arc	Nickel-based wires modified with phases of carbides, borides, silicides, etc.
	HVOF	NiCr-Cr_2C_2 type powders the with modifying agents, e.g. Cr_2C_2-NiCr and WC-Cr

2. Thermal spraying

Thermal spraying is a process where a molten material is applied onto the surface of a substrate in order to form a coating. The sprayed material in the form of wire, strip, rod or powder is heated until the partial melting and softening or the complete melting of particles. Afterwards, using a gas stream (jet) or plasma beam, the material is sprayed and directed onto a given object at high speed. Usually, the temperature of the sprayed surface does not exceed 150 °C.

Normally, thermally sprayed coatings have a thickness restricted within the range of 50 µm to 1000 µm. The microstructure of sprayed coatings depends on the spraying method (flame, arc or plasma), the composition of the sprayed coating and the parameters of the spraying process. The higher the particle deposition rate, the higher the density of the coating and its adhesion. An important element improving the adhesion of coatings is the freshly prepared, i.e. cleaned and rough, surface.

When selecting a material for spraying, the primary criteria include the requirements to be satisfied by the coating during the operation of the element onto which it has been applied, e.g.:

- corrosion resistance,
- hardness,
- resistance to cracking.

2.1. Materials used for thermal spraying

More than 100 types of thermally sprayed materials are used in industry, primarily for protection against erosion and corrosion. Arc spraying involves the use of solid and flux-cored wires, whereas HVOF processes involve the use of powders. The fabrication of materials depends on intended applications, i.e. the method of thermal spraying it will be used with. Usually, such materials are produced by liquid metal spraying, sintering and mechanical or high-temperature fusion.

The advantages of thermal spraying include the following:

- possibility of spraying materials the bonding of which to the substrate is problematic, e.g. ceramics,
- lower process temperature resulting in low stresses and strains in the workpiece,
- possibility of spraying under in-field conditions, in an air atmosphere,
- large variety of materials used in the application of coatings,
- possibility of application on heat-treated elements.

The disadvantages accompanying thermal spraying processes are the following:

- relatively low adhesion of the coating to the substrate (in comparison with that obtainable by means of surfacing);

Table 2. Basic parameters of thermal spraying

Thermal spraying	Heat source	Process temperature [°C]	Applied material	Velocity of particles impinging the substrate [m/s]	Adhesion	Efficiency [kg]
Flame with wire	Flame	3000	metals	180	medium	9
Flame with powder			metals, ceramics, polymer materials	30	low	7
HVOF			metals, carbides	600-1200	very high	14
Arc	Electric arc	5000-6000	conductive materials only	250	high	30
Plasma spraying		8000-20000	all	250-1200	high	1-25

Table 3. Selected groups of materials used in arc spraying along with their properties

Material/ Method	Material type	Composition/ Hardness [HV_{03}]	Coating properties
Wire/arc	Metcoloy 5	Fe18Cr, 8.5Mn, 5Ni, 1Si, 0.0155C	Austenitic steels with lower carbon contents, corrosion-resistant coatings
	SM8222	Fe28Cr, 5C, 1Mn	Steels with high chromium contents, coatings characterised by high hardness, wear resistance and corrosion resistance
	SM8718	Ni19, 5Cr, 18Fe, 3 Mo	Heat-resistant alloy used for regenerating alloy Inconel 718, characterised by high heat resistance and corrosion resistance up to 1000 °C
	FM-2	Fe, Al, Cr, B	Composition of intermetallic phases from the Fe-Al system, characterised by high resistance to high-temperature corrosion and abrasion
	SM 8625	Ni21, 5Cr, 8.5MO, 3Fe, 0.5 Co	Heat-resistant alloy with oxidation resistance and corrosion resistance up to 1000 °C
Powders/ flame	Metco 15 E	Ni, 17Cr, 4 Si, 4B, 3Cu, 3Mo, 2.5Fe, 0,5C	Dense coatings characterised by high wear and corrosion resistance as well as by high thermal expansion coefficient
	Metco 15 C	Ni 16Cr, 4Si, 4B, 3Cu, 3Mo, 0.5C	Coatings resistant to abrasive and erosive wear and cavitation
Carbides/HVOF	WC-Co	1100-1450	Very high resistance to abrasive and erosive wear, maximum application temperature: 773K, poor corrosion resistance
	WC-Co-Cr	1250-1450	as above + very high resistance to cavitation wear, good corrosion resistance in aqueous solutions
	Cr_2C_2-NiCr	800-1100	High resistance to erosive wear, maximum application temperature of 1173 K, good tribological properties very high corrosion resistance in gases containing sulphur, very high corrosion resistance in aqueous solutions
	Cr_2C_2- TiC-NiCr	900-1100	as above + very high resistance to erosive wear, particularly at high temperature (up to 1123 K)
	Cr_2C_2-+Mod, NiCr+Mod	900-1100	as above + very high wear resistance
	Fe-Al-FexAly	740-1100	High resistance to corrosion wear at elevated temperature
	WC-CrC-Ni	1050-1350	Very high resistance to abrasive and erosive wear, maximum application temperature of 773 K, poor corrosion resistance, very high resistance to cavitation wear, good corrosion resistance in aqueous solutions

- need for direct access to spraying equipment,
- high losses of sprayed materials,
- particles located in the peripheral areas of the jet/stream/beam move at lower speeds and undergo rapid cooling, making their adhesion to the substrate extremely low (negligible).

2.2. Application

Thermal spraying is used for:

- corrosion protection – zinc or aluminium sprayed on unalloyed steels or cast irons increases corrosion resistance, extends the service life of buildings, bridges and other structural elements. In addition, the use of high-chromium alloys on the internal surfaces of boilers makes it possible to increase the heat resistance of the latter;
- obtainment of hard coatings – thermal spraying is very often used to increase the hardness of the surface, aimed to increase its resistance to wear. Applications of this method include coatings deposited on elements of pumps, bearings, cylinders and piston rings in cars as well as on textile machinery elements;
- refurbishment of surface defects – surfaces damaged during operation can be refurbished by spraying areas containing defects in the original coating;
- fabrication of buffer coatings – spraying of primer coatings strongly bonded to the substrate makes it possible to increase adhesion. The surface of buffer coatings has varied structures, subsequently sprayed coatings are better bonded to the substrate. Another advantage of using primer coatings is the compensation of differences in thermal expansion between the substrate and the coating. Originally, the intermediate coating was made of molybdenum, which was subsequently replaced with exothermic materials such as Ni-Al alloys [8];
- decoration – often used to provide aesthetic qualities, primarily in architecture and art (sculpture);
- production of reflective coatings –mirrors are made by applying an aluminium coating onto glass [5].

3. Arc spraying

Arc spraying is the process involving the fusion of two solid or flux-cored metal wires using an electric arc having a temperature restricted within the range of 4,000 °C to 5,000 °C. The electric arc burns between two wires fed at a constant rate. During the process, a jet of compressed air sprays droplets of metal and ejects them (at very high speed) onto the object being sprayed. A standard arc spraying machine consists of a DC source, two reels feeding a wire having a thickness restricted within the range of 1 mm to 3.2 mm, a control system, a wire feeding system, a torch and an air source. The correct course of the process depends, among other things, on the precise calibration of the device so that, when coming out, the two wires could meet in the jet of air flowing out of the nozzle. The supply of current to both wires is provided by means of torch guides, made of copper alloy.

3.1. Arc spraying process

3.1.1. Description of the technology

The process of arc spraying requires thorough preparation of the workpiece surface, usually by sandblasting or, in cases of painted surfaces, through water jet washing. When spraying a coating thicker than 1.0 mm, it is recommended to make an intermediate coating of nickel or manganese steel. Because arc spraying involves the simultaneous melting of two wires, it is possible to obtain coatings from mixtures of metals, without the necessity of spraying with flux-cored wire.

Arc ignition is caused by the flow of a very high current, restricted within the range of 50 A to 500 A, generating a very large amount of heat on contact resistances. Arc voltage ranges from 18 V to 40 V. Compressed air flowing out of the nozzle has a pressure restricted within the range of 2 bar to 7 bar and a flow rate restricted within the range of 2 m^3/min to 5 m^3/min. Such parameters allow the transfer of the wire to the element subjected to spraying at a rate restricted within the range of 150 m/s to 200 m/s. The oscillatory nature of arc burning enables the ejection of equally-sized particles, which, impinging the substrate at very high temperatures adhere evenly to the substrate and fill in irregularities. The high temperature of particles enables the obtainment of metallic bonds joining the coating with the substrate.

However, the high temperature of the arc and the high flow rate of air may lead to the evaporation or oxidation of the material being sprayed. In order to achieve the homogeneous composition of the coating it is often necessary to use an external nozzle containing a shielding gas (used to prevent the oxidation of the surface).

3.2. Spraying parameters

Surface preparation is a very important activity, significantly affecting the adhesion of sprayed coatings. Usually, surfaces are prepared by sandblasting as this process enables the obtainment of appropriate roughness and makes it possible to clean the surface of the element to be sprayed.

The type of the material and the diameter of the wire are parameters determining the performance and quality of coatings. Higher melting points of metals enable the use of greater wire diameters.

Voltage is a parameter determining the amount of thermal energy emitted in the arc and the width of the gap between the wires. Excessively high voltage is responsible for arc instability, whereas overly low voltage could lead to the shorting of the wires.

Current (intensity) is a factor fundamentally affecting the wire melting rate and, consequently, the efficiency of the spraying process. Current also determines the temperature of sprayed particles, which is closely related to the strength of the joint between the substrate and the coating and significantly affects the porosity of the coating. Table 4 presents the effect of current on the efficiency of the process performed using wires having a diameter of 2.4 mm.

Gas pressure and output are factors the adjustment of which affects the porosity of coatings. Excessive porosity of the sprayed coating is caused by the overly low pressure of the spray gas.

The distance between the surface and the torch has a significant effect on the heating of the element, the porosity and oxidation of the coating and on spraying efficiency. Shorter distances from the workpiece enable the obtainment of coating characterised by superior quality, whereas longer distances from the workpiece surface increase the efficiency of the spraying process.

Arc spraying is a versatile process and can be performed both manually and automatically (robotically). The freedom of method application also concerns materials onto which the coating can be deposited, i.e.:

- metal structures,
- ceramics (including concrete and glass),
- thermoplastics,
- wood.

The versatility of the method allows spraying objects of any shape and size. The technological development of

Table 4. Arc spraying efficiency as a function of current

Type of wire material	Spraying capacity in kg/h vs. current value					
	50 A	100 A	150 A	200 A	250 A	300 A
Aluminium	2.6	3.7	4.7	5.7	6.7	7.8
Copper	3.0	6.7	10.4	14.0	17.7	21.4
Monel	3.2	5.8	8.5	11.0	13.8	16.5
Nickel	2.0	4.3	6.6	8.8	11.1	13.4
Cr-Ni steels	2.9	5.7	8.4	11.3	14.0	16.7
C-Mn steels	2.3	4.7	7.2	9.7	12.2	14.7
Zinc	4.5	9.5	14.5	19.5	24.5	29.2

spray guns enables the arc spraying of internal surfaces of pipes and cylinders, making this method frequently chosen by automotive companies. Method-related innovations are also concerned with wire feeders, which, owing to the possibility of moving the gun away from the feeder by as many as 12 meters, enables the performance of the spraying process in poorly accessible areas and protective booths, the access to which with the entire spraying equipment would be impossible.

3.3. Flux-cored wires in thermal spraying

The development of flux-cored wires for arc spraying has greatly expanded the applicability of this process in industry. In many cases, the method of arc spraying of coatings by means of flux-cored wires makes it possible to obtain coatings comparable with those sprayed using plasma or supersonic methods at much lower manufacturing costs. The use of material in the wire form simplifies its use and lowers the cost of the process if compared with powder materials. One of the disadvantages of the process is the applicability of coatings conducting electric current. However, the aforementioned disadvantage can be eliminated by using wires consisting of a conductive cover and a non-conductive core (e.g. carbides or nitrides). Because of the fact that flux-cored wires melt without forming alloys, it is possible to make a wide range of coatings. Table 5 presents examples of flux-cored wires along with their properties and suggested applications.

In arc spraying processes, flux-cored wires are used to make:

- amorphous coatings in the iron matrix, containing chromium, nickel and molybdenum, resistant to abrasion;
- ceramic coatings in the nickel matrix with additions of chromium, molybdenum and aluminium, used as primer coatings in aircraft engines;
- $Fe\text{-}Fe_3O_4/Ni\text{-}NiO\text{-}CrO$ cermet coatings used in the spraying of combustion engine valve seats, increasing their service life by several times;
- cermet coatings in the aluminium matrix containing 10 % Al_2O_3, used in the production of anti-slip mats of aircraft carrier landing pads, extending their service life five-fold and reducing the cost of production by 20 % if compared with previously used polymer coatings [9];
- coatings consisting of nitrides, carbides or oxides embedded in the soft matrix.

3.4. Applications of spraying in industry

Arc spraying has found many applications in industry, improving the surface properties of elements, including the following:

- **pneumatics** – flux-cored wires are used to refurbish turbine shafts and gas pump compressors as well as rods of hydraulic motors in mining machinery [9];
- **coatings used inside boilers** – because of the high exposure of furnace chambers to erosive wear, the most effective method is the thermal spraying of coatings containing chromium carbides, characterised by favourable properties, i.e. high resistance to abrasive and erosive wear (particularly at high temperature) and good abrasive wear resistance, enabling operation at temperatures of up to 850 °C. In the above-named application, the method proves successful because of the relatively inexpensive costs of coating fabrication, appropriate properties allowing the extension of the service life of furnaces and the refurbishment of elements without the necessity of replacing the boiler [16];
- **shipbuilding industry** – zinc or aluminium alloy coatings used for coating ship structures and platforms (rigs) exposed to harmful effects of seawater, providing the aforesaid structures with a lifespan of up to 20 years;
- **rapid prototyping** – arc-sprayed coatings have also found applications in rapid prototyping technologies, involving the representation of a finished element serving as a model. The element reproduced in a ceramic mould is sprayed with an iron coating, increasing the accuracy

Table 5. Examples of flux-cored wires used for spraying and their parameters

Type of flux-cored wire	Properties of coatings	Application
Cr6Al8B3	HRC = 40 HV = 650 Strength: -cohesive = 130 MPa -adhesive 40 MPa	refurbishment of necks of moderately loaded crankshafts, timing gear, protection of printing equipment against abrasive wear
50Cr6Al3Mn2Mo2C2	HV =350 Strength: – cohesive = 180 MPa – adhesive 40 MPa	refurbishment of bearing parts
Cr6Al6B3Ni4	HRC = 40 HV = 1000 Strength: – cohesive= 60 MPa – adhesive 45 MPa	protection against abrasive-gas wear and gas corrosion at high temperature (up to 700 °C)
70Cr6Al6B3W4	HRC = 40 HV = 1150 Strength: – cohesive = 60 MPa – adhesive 45 MPa	protection against abrasive-gas wear and high-temperature gas corrosion at high temperature (up to 600 °C)
50Cr6Al2Mn2Ti2Mo2	HV = 500 Strength: – cohesive = 180 MPa – adhesive 40 MPa	refurbishment of shaft necks and timing gear

and durability of such a mould. The method is used in low-volume production [13],

- **automotive industry** – high efficiency of the method along with the high quality of sprayed coatings is responsible for the popularity of the method in the automotive industry (mainly arc or plasma spraying processes). The results of 300 hours' testing of plasma-sprayed coatings with a material developed by Sulzer Metco revealed that the use of the coating sprayed onto a cast iron bushing made it possible to reduce the wear of the latter from 1.2 nm/h to 0.66 nm/h.

Other tests involved aluminium cylinders, where, after the application of the material, whose chemical composition is presented in Table 6, the rigidity of engine blocks with the sprayed coating exceeded that of cast iron cylinders. As a result, the loss of weight during corrosion tests was reduced by four times if compared with classic, i.e. cast iron cylinders.

Mercedes, on the other hand, uses an arc spraying method known as "nanoslide". This method is applied in the most powerful engines available from this manufacturer, i.e. the 63 AMG engine having a cubic capacity of 6.3 litres as well as 3-litre V6 turbocharged engines. After spraying, the cylinder surface is subjected to smoothing, which decreases friction by 50 % if compared to that present in grey iron bushings and, in addition, reduces the consumption of fuel by 3 %. Table 7 presents the remaining types of engines with service life extended by using welding-based coating application methods.

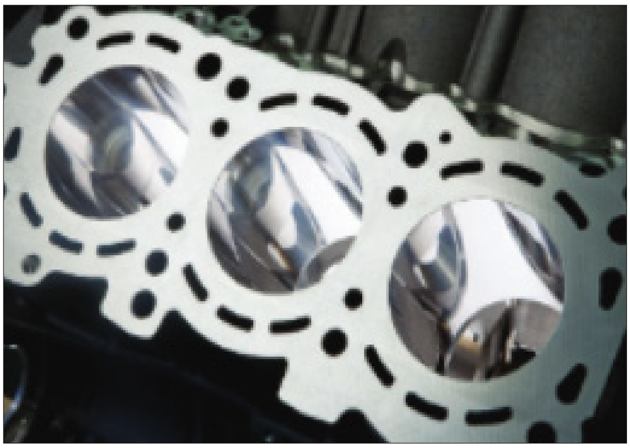


Fig. 4. Gliding surface obtained on the cylindrical surface of the 63 AMG engine cylinder

Another application involves the GMA method-based spraying of weld surfaces aimed at filling irregularities and porosity in joints with silicon bronze coatings:

- **concrete structures** – studies have shown that the deposition of zinc coatings on concrete can extend the life of concrete structures by as many as 20 years. The thickness of the above-named arc-sprayed coatings is restricted within the range of 0.3 mm to 0.5 mm. Such coatings are economically justified in relation to a capacity of approximately 100 kg/h. The application areas of the method include the construction of roads and bridges as well as platforms exposed to the harmful effect of moisture (water vapour);
- **rapid tooling** – intensive development of the arc spraying method involving the use of flux-cored wires has extended the application area of the former. The Tafa company has used a method where 3 automated and computer-controlled robots spray a tool mould additionally fusing lead wires, which, after melting, shaped channels cooling the body being less than 20 mm thick. In such a way, it is possible to reduce four-fold the time needed for the preparation of the die block in comparison with the previously used technology.

4. Individual study

4.1. Testing materials and methodology

The tests discussed in the remainder of the article were performed to compare the erosion resistance, roughness and hardness of coatings arc-sprayed using EuTronic Arc 599 and EuTronic Arc 595 flux-cored wires on unalloyed

Table 6. Chemical composition of the coating sprayed on the aluminium cylinder

Percentage chemical composition of the flux (powder), [%]										
C	Si	Mn	P	S	Ni	Cr	Cu	V	B	Fe
3.10	2.89	0.08	0.004	0.004	8.95	2.46	4.80	0.74	0.075	reszta

Table 7. Other internal combustion engines using thermally sprayed cylinder coatings [6]

Engine type	Number of cylinders	Car model
Petrol engines		
Lupo FSI 1.4L	4	VW Lupo
Swiss Auto Biland	2	Karting racing
Bugatti W16	16	Bugatti
V 10	10	Formula 1 racing
V8	8	Formula 1 racing
V4	4	Motorbike racing
Diesel engines		
V10 TDI (VW)	10	Touareg, Phaeton
L 5 Ea115 (VW)	5	Touareg, Van T5

steel ASTM A516 Gr. 55. The spraying process was performed in accordance with the EN ISO 14923 standard.

The coating was sprayed using a stand equipped with a EuTronic Arc Spray 4 machine. Before the spraying process, the steel plate onto which the coating was applied had been subjected to shot blasting and heating to a temperature of 40 °C.

Fig. 5. EuTronic Arc Spray 4 arc spraying device (Castolin)

Table 8 presents the chemical composition, coating hardness and spraying parameters

4.2. Badanie twardości

The study-related analyses included the performance of Vickers test-based micro-hardness measurements performed in accordance with the PN-EN ISO 6507-1 standard. The purpose of the tests was to identify the hardness of the sprayed coating, heat affected zone (the substrate) and of the base material. The tests were performed using a Micro Vickers 401 MVD microhardness tester (Wilson Wolpert). The machine was equipped with a microscope enabling the precise identification of areas subjected to the hardness tests.

The hardness of coatings is an important factor when selecting a material for spraying and is often one of the primary parameters taken into consideration when designing a given element. During the Vickers micro-hardness tests it was necessary to bevel the substrate of the test specimen and clamp it in special grips, maximally blocking the compensation of the force used in the test (caused by the plastic deformation of the resin in which the specimen was included). Otherwise, the hardness results would have been underestimated, as was the case with the first approach to the hardness tests. The results of microhardness measurements are presented in Table 9.

The tests revealed that the hardness of the coating was significantly higher than that of the base material and amounted to, on average, 821.4 HV in relation to the EuTronic Arc 599 coating (indicating a fourfold increase in hardness compared to the base material (402 %)) and 755.6 HV in relation to the EuTronic Arc 595 coating (i.e. a 360 % increase in hardness if compared with that of the base material).

4.3. Roughness tests

The examination of the texture of the sprayed coatings required identification of surface roughness. The tests

Table 8. Spraying parameters

Filler metal designation	Chemical composition, density and hardness of the coating	Spraying parameters		
		Current [A]	Voltage [V]	Distance between the gun and the area subjected to spraying, [mm]
EuTronic Arc 595	Fe – 25-29 %, Cr 3-4 %, B – 1-2 %, Si 1-2 %, Mn; hardness of the coating: 60 HRC; coating density: 5.8857 g/cm^3	200	33	180
EuTronic Arc 599	Ni – WC – Cr – B – C (detailed composition withheld by the manufacturer as proprietary) matrix hardness: 820 HV WC hardness: 2400 HV coating density: 8.7854 g/cm^3	200	30	180

Table 9. Microhardness measurement results in different areas of the specimen

Measurement number	Microhardness of the base material [HV]		Microhardness of the HAZ [HV]		Microhardness of the coating [HV]	
	EuTronic Arc 599	EuTronic Arc 595	EuTronic Arc 599	EuTronic Arc 595	EuTronic Arc 599	EuTronic Arc 595
No. 1	167	170	197	195	803	760
No. 2	159	159	201	198	841	688
No. 3	164	165	194	203	816	850
No. 4	161	168	193	200	831	883
No. 5	166	159	196	199	816	597
Mean	163.4	164.2	196.2	199	821.4	755.6

were performed using an SJ-210 surface tester (Mitutoyo) and dedicated Surftest SJ-210 Communication Ver 4.001 software. The roughness tests, involving both test specimens, were performed in accordance with the PN-EN ISO 4287 standard; the length of the measurement segment amounted to 0.8 mm.

The areas subjected to the tests were and presented in Figure 6 were performed:

- for measurement segments 1, 2 and 3 – along the specimen
- for measurement segments 4 and 5 – transversely.

Table 10 presents the roughness test results in relation to 2 parameters, i.e. the arithmetic mean deviation of the profile from the mean line (*Ra*) and the sum of the arithmetic mean height of the five highest peaks above the mean line and the mean depth of the five lowest valleys below the mean line.

The results obtained in the roughness tests in relation both specimens were different, which could be ascribed to the presence of tungsten carbides in the Eutronic Arc 599 coating. It was also possible that, in one case, the spraying parameters applied in the test led to the partial melting of the material, whereas in the other case, they only led to the plasticisation of the material. Within one specimen, the roughness values were very similar, both in relation to the parameter of mean deviation and the highest roughness amplitudes. The foregoing revealed the stability of the process as well as its steady performance (i.e. the smooth movement of the spray gun in relation to the substrate). Figure 7 presents the roughness of the specimen in the linear area of the test.

Fig. 6. Areas subjected to the roughness tests

Table 10. Results of coating roughness measurements

Specimen no.	Eutronic Arc 599		Eutronic Arc 595	
	***Ra*, [μm]**	***Rz*, [μm]**	***Ra*, [μm]**	***Rz*, [μm]**
1	15.858	74.453	12.325	66.258
2	16.042	75.736	11.979	64.461
3	15.746	75.26	12.179	67.025
4	15.835	75.424	12.628	64.566
5	17.131	82.641	12.630	65.541
Mean value	16.122	76.703	12.345	65.570

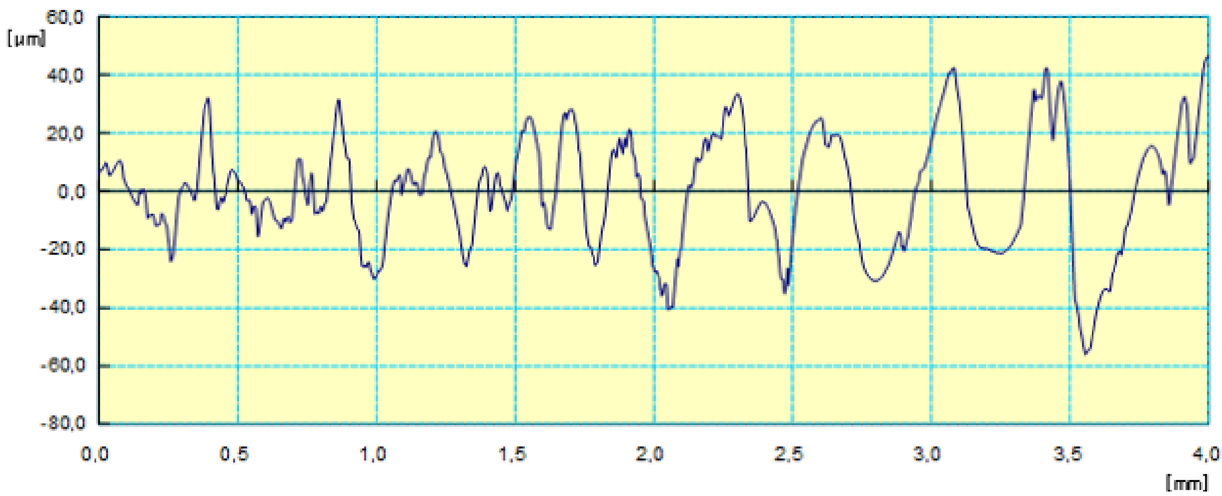


Fig. 7. Linear roughness of the EuTronic Arc coating

4.4. Erosion tests

The determination of the erosion resistance of the coatings required the performance of erosion tests (conducted in accordance with the recommendations of the ASTM – G 76-2 standard) using the test stand presented in Figure 8. The erosion tests concerning the arc-sprayed coatings were performed in relation to three erodent angles of incidence, i.e. 30°, 60° and 90°. Before the tests, the testing device was calibrated and the specimens were weighed in order to determine the weight decrement during the tests. Table 11 presents the parameters of the erosion tests.

The determination of erosion resistance also involved referring to steel HARDOX 400, characterised by very high erosion resistance, often used for making bulldozer blades, self-loading trailer casings, sieves and bar screens as well as housings for hydraulic hammers, gravel chutes and excavator buckets. The foregoing made it possible to identify the applicability of materials provided with a given coating in industry. The identification of erosion resistance following the requirements of the ASTM G 76-2 standard necessitated testing the density of the coating. In turn, the determination of erosion resistance required testing the density of the coatings performed using a hydrostatic balance.

Table 11. Parameters of the erosion test

Parameters of the erosion test	
Erodent speed	702 m/s
Temperature	20 °C
Erodent	Al_2O_3
Type of carrier gas	compressed air
Size of erodent particles	45–70 µm
Amount of erodent fed	2.1 g/min
Test time	10 min.
Distance between the nozzle and the specimen	10 mm.

The tests results were as follows:

- EuTronic Arc 599 coating density – 8.7854 g/cm^3,
- EuTronic Arc 595 coating density – 5.8857 g/cm^3.

Table 12 presents the erosion test results.

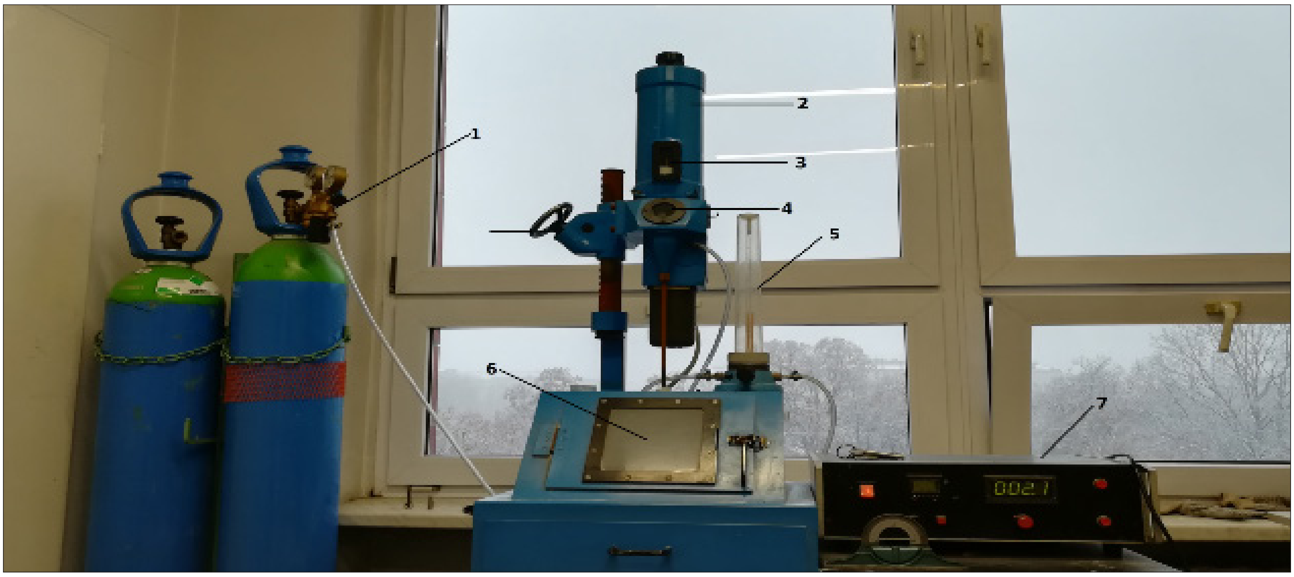


Fig. 8. Test stand used in the erosion resistance tests: 1 – air cylinder regulator, 2 – erodent tank, 3 – sight glass for checking the level of erodent, 4 – sight glass for checking the continuity of erodent feeding, 5 – rotameter, 6 – measurement chamber and 7 – control and adjustment unit

Table 12. Erosion test results

Specimen designation	Erodent angle of incidence	Mass decrement [g]	Erosion rate [g/min]	Volume decrement [mm^3]	Erosive wear resistance [0.001 mm^3/g]	Relative erosion resistance*
EuTronic Arc 599	90°	0.0140	0.00140	1.59355	78.69382	0.518
	60°	0.0152	0.00152	1.73014	85.43901	0.547
	30°	0.0138	0.00138	1.57078	77.56938	0.611
EuTronic Arc 595	90°	0.0087	0.00094	1.54612	76.35160	0.534
	60°	0.0093	0.00101	1.71692	84.78617	0.551
	30°	0.0090	0.00099	1.52912	75.51209	0.627
Hardox 400	90°	0.0065	0.00065	0.82582	40.7862	1
	60°	0.0070	0.00070	0.83863	46.7473	1
	30°	0.0072	0.00072	0.81321	47.3748	1

Notes: Erosion rate [g/min] = specimen mass decrement [mg]: exposure time [min]; erosion resistance [0.001 mm^3/g] = specimen volume decrement [mm^3]: total mass of erodent used in the specimen [g]

The erosion tests revealed that the EuTronic Arc 595 coating, despite its lower hardness, was characterised by slightly higher erosion resistance in comparison with that of the EuTronic Arc 599 coating. Such a situation could be ascribed to overly low spraying parameters, the use of which only plasticised the filler metal in the form of the flux-cored wire additive material, without partially melting it. However, both coatings were characterised by relatively high erosion resistance, indicating (in certain economically justified situations) the usability of the coatings in providing materials with erosion protection. Because of the fact that the price of steel Hardox 400 steel is relatively high, the use of the EuTronic Arc coatings seems fully justified in situations where an erosive environment is not aggressive enough to wear out the coating.

Figures 10-12 showing the appearance of the coating after the erosion in relation to an erodent angle of incidence of 90°, 30° and 60° respectively.

The photographs revealed the reduced roughness of the surface, resulting from the effect of the erodent on the coating. The fact that no base material was observed indicated the proper performance of the process and that the only mass decrement was that of the coating.

4.5. Metallographic tests

The identification of the thickness of the sprayed coatings and structural observations required the performance of macro and microscopic metallographic tests. The observations were performed using a GX 71 microscope (Olympus).

The thickness of the arc-sprayed coatings was identified using metallographic specimens (in accordance with the PN-EN ISO 1463 standard). Figures 13 and 14 present the thicknesses of the coatings.

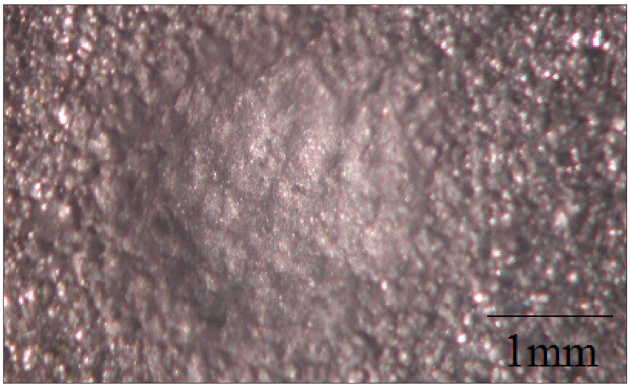


Fig. 10. Specimen after the erosion test in relation to an incidence angle of 90°

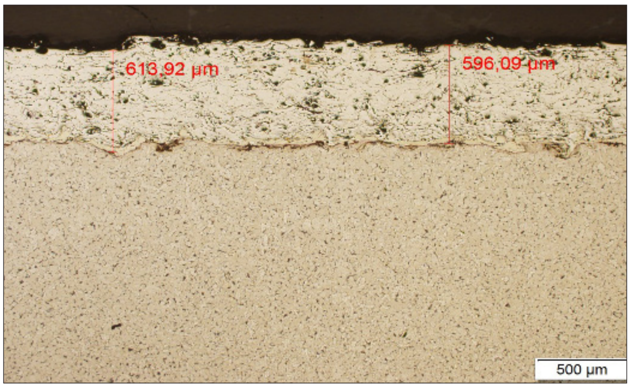


Fig. 13. Thickness of the coating sprayed with the EuTronic Arc 595 flux-cored wire

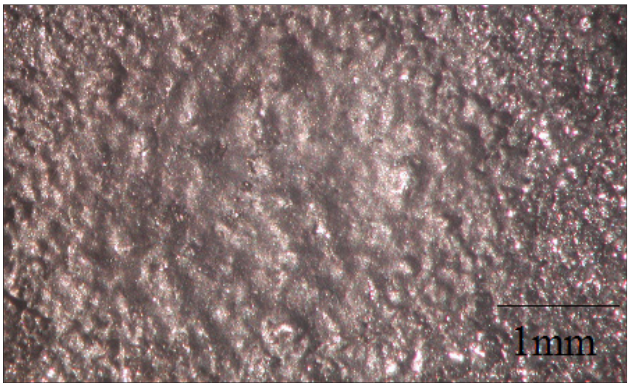


Fig. 11. Specimen after the erosion test in relation to an incidence angle of 30°

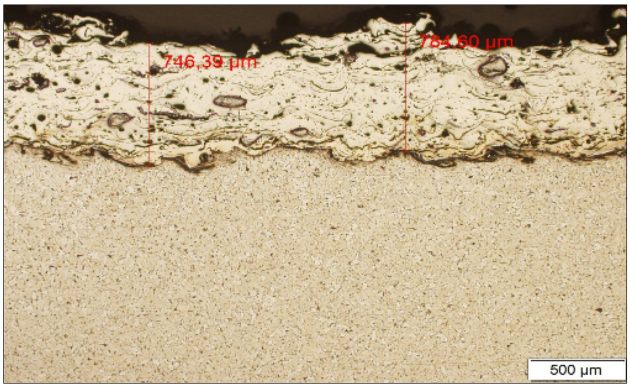


Fig. 14. Thickness of the coating sprayed with the EuTronic Arc 599 flux-cored wire

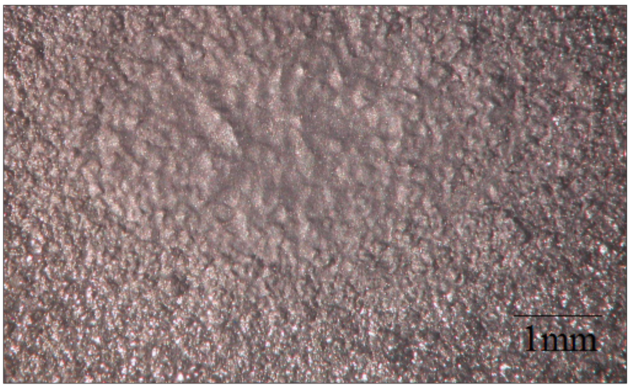


Fig. 12. Specimen after the erosion test in relation to an incidence angle of 60°

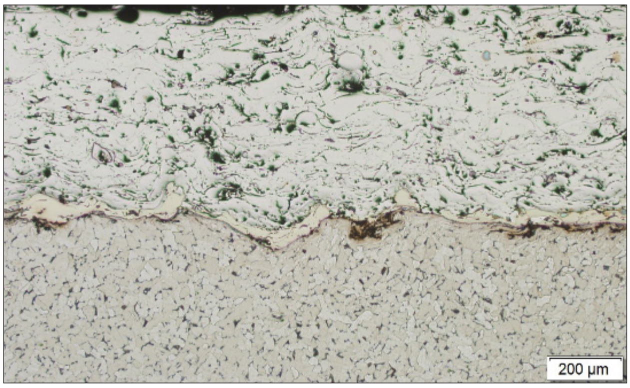


Fig. 15. EuTronic Arc 595 coating magnified 100×

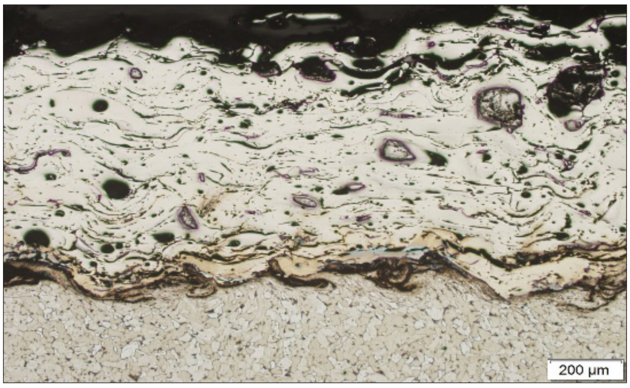


Fig. 16. Eutronic Arc 599 coating magnified 100×

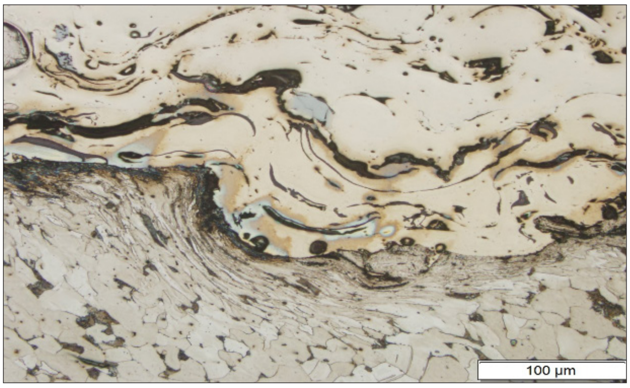


Fig. 20. EuTronic Arc 599 coating microstructure magnified 400×

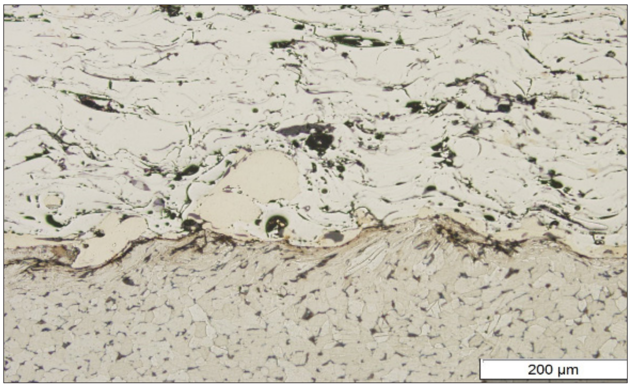


Fig. 17. EuTronic Arc 595 coating magnified 200×

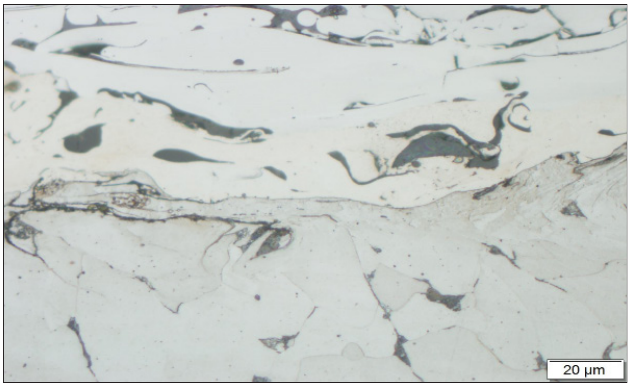


Fig. 21. EuTronic Arc 595 coating microstructure magnified 1000×

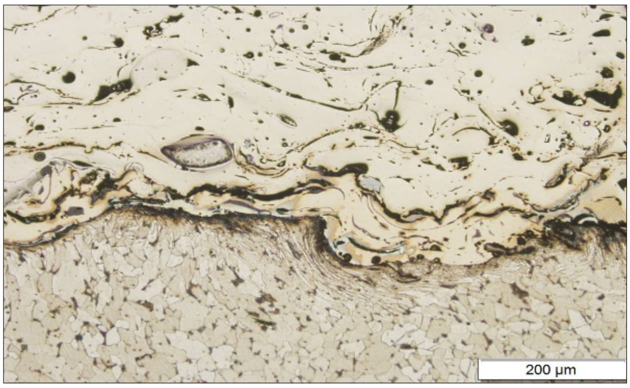
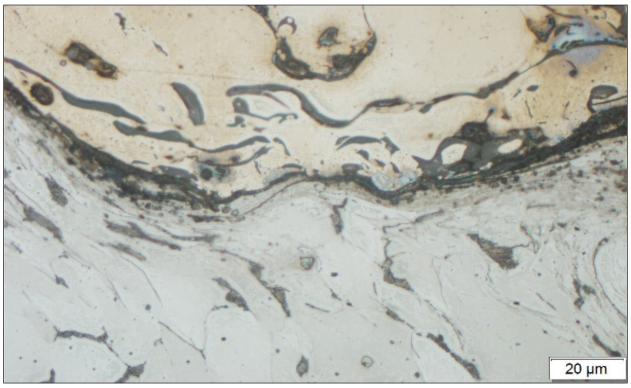


Fig. 18. EuTronic Arc 599 coating microstructure magnified 200×



Rys. 22. Widok mikrostruktury próbki EuTronic Arc 599 w powiększeniu ×1000

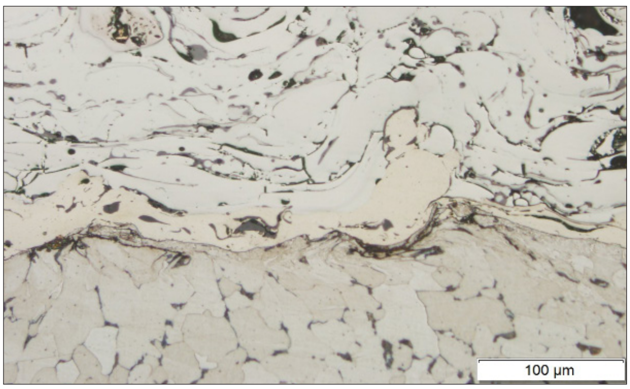


Fig. 19. EuTronic Arc 595 coating microstructure magnified 400×

5. Analysis of test results

The analysis of the hardness test results revealed that the EuTronic Arc coatings were characterised by very high hardness. The mean hardness of the EuTronic Arc 595 coating amounted to 755 HV, whereas the mean hardness of the EuTronic Arc 599 coating amounted to 821 HV. As can be seen, the application of the coatings increased the hardness (in relation to that of the base material) by 360 % and 401 % respectively. The EuTronic Arc 599 coating was characterised by a significantly higher mean roughness of 16.12 µm if compared to that of the EuTronic Arc 595 coating, amounting to 12.35 µm. The aforesaid situation could be ascribed to the greater plasticisation of the material during spraying (in terms of the EuTronic Arc 595 coating).

The erosion tests revealed that both the EuTronic Arc 595 and EuTronic Arc 599 coatings were characterised by similar erosion resistance, constituting 55 % and 57 % (respectively) of steel Hardox 400 erosion resistance. The foregoing indicates that the Eutronic Arc 595 coating was characterised by higher erosion resistance and lower hardness in comparison with that of the other coating. The erosion test did not result in the penetration of the base material by the erodent. The measurements of sprayed coating thicknesses revealed that the EuTronic Arc 595 coating was approximately 0.6 mm thick, whereas the thickness of the EuTronic Arc 599 coating amounted to 0.78 mm.

At the boundary between the base material and the sprayed coating, it was possible to observe changes in the structure of the base material. The ferrite and pearlite grains of the low-carbon steel were significantly elongated and flattened in the direction perpendicular to the axis of spraying; similar situation was observed in relation to cold rolling. The foregoing indicates the very high force with which the particles impinged the base material, exceeding the critical strain without the direct application of pressure. The observation revealed that the closed porosity of the specimens was relatively low.

The shape of the sprayed particles varied greatly, which was probably triggered by the partial melting of some phases, which "adapted" to the substrate, forming flat grains, whereas the harder and less plasticised phases remained spheroidal.

6. Conclusions

- Arc-sprayed EuTronic Arc coatings are characterised by parameters enabling the use of the former in moderately aggressive erosion environments, where it is economically justified to replace steel Hardox 400 with conventional carbon steel enriched with the EuTronic Arc type coating.
- Arc-sprayed EuTronic Arc coatings enable the obtainment of hard and erosion-resistant coating characterised by low porosity.
- Roughness *Ra* of the arc-sprayed coatings amounted to, on average, 12.35 μm in terms of the EuTronic Arc 595 coating, and 16.12 μm as regards the EuTronic Arc 599 coating. The greater roughness of the EuTronic Arc 599 coating was probably triggered by the lower plasticisation of the sprayed material. In cases requiring the formation of a smooth surface it would be necessary to obtain a thicker coating and subsequently subject it to surface processing (e.g. grinding).
- EuTronic Arc 599 and EuTronic Arc 595 coatings were characterised by similar erosion resistance parameters, accounting for 55 % and 57 % of the erosion resistance of steel Hardox 400.
- EuTronic Arc 595 coating was characterised by the more varied hardness of the phases present in the coating if compared with of the EuTronic Arc 599 coating.
- The energy of the arc-sprayed particles was sufficiently high to trigger the deformation of the base material.

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