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Adhesion of FeCrNiBSi–(W–Ti)C wire-arc deposited coatings onto carbon steel substrates determined by indentation measurements and modeling

Yazid Fizi [a,b], Yamina Mebdoua [a,*], Hadj Lahmar [a], Sofiane Djeraf [c], Saci Benbahouche [b]

[a] Centre de Développement des Technologies Avancées CDTA, Cité 20 août 1956, BP.17 Baba Hassen, Alger, Algeria
[b] Laboratoire de Mécanique de Précision Appliquée, Département d'optique et de Mécanique de Précision, Université Ferhat Abbas UFAS, Sétif, Algeria
[c] Ecole Nationale Polytechnique ENP, 10 Avenue Frères Oudec, Hassen Badi, BP.182, 16200, El Harrach, Alger, Algeria

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ABSTRACT

Wire-arc-sprayed coatings are widely used to protect industrial parts mainly from wear and erosion. The present work combines experimental measurements performed by instrumented indentation and their modeling in order to determine the elastic–plastic behavior of a wire-arc sprayed FeCrNiBSi–(W–Ti)C using Metco 8297 cored wire as feedstock material. The coating was sprayed onto low carbon steel (C35) substrate after cleaning and grit blasting. The elastic–plastic behavior law optimized from instrumented indentation tests allowed calculating the coating adhesion. The effect of the displacement velocity of the tensile test on the fracture resistance was also investigated.

1. Introduction

Wire-arc spraying (WAS) process using cored wire feedstock has found large industrial applications in hard surfacing, especially where wear and erosion resistances are important. Cored wires with a ductile metal or alloy envelope containing hard particles have extended the use of WAS to broader fields previously dominated by other processes such as plasma and HVOF spraying [1]. The commercial cored wire Metco 8297 [2] is used in this study for surface protection against wear [3] of drilling tools in Algerian mining industry.

In wire-arc spraying process, an electric arc is created between two consumable conductive wires, continuously advanced, the high temperature of the arc melting the wire tips, while a gas flow propels the molten particles toward the substrate surface to be coated. Each droplet spreads on the substrate upon impact and solidifies forming a splat. The coating results from the layering of the deposited splats and presents lamellar structure with the inclusion of oxides, pores, cracks, and unmolten particles. Besides the intrinsic properties of sprayed material, the quality and properties of coatings depend strongly on splat/substrate and splat/splat interfaces.

In order to achieve reliable and reproducible coatings, their microstructure and mechanical properties must be characterized. Among the different properties, the aim of this work is to determine the coating adhesion using instrumented indentation measurements.

Adhesion strength of thermal-sprayed coatings is of crucial importance in many industrial applications, as it influences the performance of produced coatings such as the impact resistance, fatigue life, and even corrosion resistance [4,5]. Numerous testing methods exist to measure the adhesion strength and interfacial fracture toughness of coatings, such as pin test, shear adhesion test, bending test, peeling test, double cantilever beam (DCB) test and interfacial indentation test [6–14]. However, tests adapted to a given coating system are not necessarily suited to another one [15,16]. The tensile adhesion test is the most commonly used one thanks to its ease of use compared to other methods. In the conventional tensile adhesion testing methods such as those standardized in ISO 14916:1999, ASTM C633-79, and JIS H 8402:2004, the coated sample (a cylinder with a diameter of 25.4 mm × 25.4 mm long) is glued to an uncoated similar counterpart that is just grit blasted and then tested in tension in a universal testing machine [17,18]. Even though, this type of testing has been most widely used, there are cases in which measurement of adhesive strength of the sprayed coating is difficult, for example when the coating adhesion is higher than that of the glue.

One of the other methods widely used for such measurements is depth-sensing indentation at low load; often termed Instrumented Indentation Test (IIT). This method has been employed by many researchers in order to investigate the elastic and plastic properties of materials [19–23]. In recent years, different methods, based on both experimental and numerical studies, have been proposed to extract the elastic–plastic properties from the indentation data. Cheng and Cheng [24,25] used dimensional and finite element analysis to evaluate the mechanical properties of the materials from conical indentation tests. Giannakopoulos and Suresh [26] proposed an alternative method based on displacement and energy approaches to determine Young's modulus, yield strength, and microhardness from the loading part of the indentation curve and the indentation depth after unloading.

* Corresponding author at: Centre de Développement des Technologies Avancées, Cité 20 août 1956, 16303, Baba Hassen, Alger, Algeria.
E-mail address: ymebdoua@cdta.dz (Y. Mebdoua).

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Table 1
Arc spraying parameters.

Voltage (V)	36
Current (A)	100
Spray distance (mm)	100, 120, 140
Air pressure (MPa)	0.38

Table 2
Chemical composition of cored wire and substrate (mass friction, %).

	TiC	Cr	Mn	Ni	WC	Cu	B	Si	Fe
Cored wire	5.	14.		5.	25.		1.5	1	Bal.
C35		0.17	0.792	0.198		0.163			Bal.

However, their method failed to resolve the issue of uniqueness. More recently, Tunvisut et al. [27,28] employed dimensional analysis and finite element techniques to determine the relationships between Young's modulus, yield strength, and strain hardening for both elastic–plastic substrate and coating materials.

Due to the difficulty of conducting conventional tensile test when the glue was not strong enough, a numerical approach was adopted combining instrumented indentation measurements and their modeling. Three elastic–plastic parameters (yield stress σ_y, strength coefficient K and work hardening exponent n) were extracted in a non-linear optimization approach, fully integrated with finite element (FE) analysis, using a single indentation curve. These optimized elastic–plastic parameters of the material, allowed the simulation of the coating adhesion. The iteration procedure of optimization was based on a nonlinear least-squares method implemented in MATLAB® where result file was created to automatically update the plastic material properties of a power-law material in ABAQUS® software input file and then ABAQUS® was run to obtain a loading–unloading curve, which was compared to the experimental one.

2. Wire-arc sprayed coating

In this work, a twin wire arc spraying facility of Algerian company (using ArcSpray 234 model from Metallization Company) was used to spray FeCrNiBSi–(W–Ti)C coating on low carbon steel, the cored wire Metco 8297 with a diameter of 1.6 mm being used as feedstock material. The spray parameters are presented in Table 1 based on previous studies retaining the spray distance as the main parameter. The latter has an important role on the in-flight particle oxidation. As the oxidation rate of the inflight particles is higher as their residence time in the jet is longer, it provides additional heat and delays the particle cooling. The coatings were sprayed on the top of steel substrates (C35) of cylindrical shape 25 mm in diameter and 5 mm in thickness, after cleaning and grit blasting using corundum abrasive particles. The mean roughness, Ra, of the substrate surface after blasting was 6 μm. The chemical composition of the substrate and that of the cored wire is presented in Table 2.

3. Measurements

Microscopic observations were performed on coating cross-sections using optical and electronic microscopies. The samples were ground using series of SiC papers 400, 600, 800, 1000 and 1200 grit, and finally polished with 1 μm alumina particles. The coating thickness was measured by profile projector MP320 10× in different positions in the IIT1, IIT2 and IIT3 corresponding to the samples achieved at spray distances of 100 mm, 120 mm and 140 mm respectively. The average coating thicknesses obtained from ten measurements were 386 $\pm$ 23, 416 $\pm$ 12 and 460 $\pm$ 48 μm, respectively. SEM observations of the coating microstructure and porosity evaluation were obtained using JEOL JDX-3530 LV Scanning Electron Microscope (SEM), with the resolution of 3.0 mm, magnification of $\times$5 to $\times$300,000 and accelerating voltage of 3 to 30 kV. Porosity percentage was evaluated using image analysis with Image-J program. The obtained images were threshold to form binary images with pores in black and materials in white. The porosity measured for the three samples is presented in Table 3. Elemental analysis of the coating was carried out using energy dispersive spectroscopy (EDS).

Instrumented indentation measurements were also performed on the coating cross-sections of the three examined samples in order to obtain experimental load–displacement curves of the composite coating. For these measurements micro-indenter Z2.5 with a Vickers tip was used with Zwick/Roell equipment, which resolutions were $\pm$0.01% in force and 0.02 μm in displacement. The experiment involved a controlled displacement with an indentation velocity of 8.3 μm/s. When the maximum available depth was reached, the indenter was held for 15 s, and then moved back with the same velocity. A Vickers indenter with a maximum load of 5 N was used. The maximum indentation depth from different tests was approximately 7 μm. The depth-sensing indentation measurement was used to determine the microhardness and the Young's modulus. The microhardness, H_{IT}, was evaluated using Oliver and Pharr relationship [29]:

$$H_{IT} = \frac{P_{max}}{A_p} \tag{1}$$

where P_{max} is the maximum applied load and A_p is the projected contact area of the indentation at the maximum load.

The mechanical properties measured using IIT1, IIT2 and IIT3 tests are illustrated in Table 3. The resulting values represent the average of ten measurements for each test. Microhardness H_{IT} is defined by the projected contact area (A_p), and the second, H_V, by the contact area (A_s). The difference between H_V and H_{IT} in Table 3 is explained by the following equation:

$$H_V = \frac{1}{g}\frac{A_p}{A_s} H_{IT} \tag{2}$$

where g is the acceleration of gravity: 9.80665 $m \cdot s^{-2}$, $\frac{A_p}{A_s} = 0.9270$.

Tensile bond strength tests were carried out, in this study, following requirements stated in the standard ASTM C633-79 and the Zwick/Roell Z.100 equipment. The test specimens consisted of a pair of C35 steel cylindrical stubs, 25.4 mm in diameter and 25 mm in thickness. A pair of the test stubs, one wire arc coated with a commercial cored wire Metco 8297 and the other uncoated but grit blasted and degreased, was bonded together with FM1000 adhesive film to form the tensile bond strength test specimen. Then they were pulled to fracture in a screw-driven universal testing machine at a displacement rate of 0.84 $mm \cdot min^{-1}$.

Table 3
Mechanical properties measured from the IIT.

	H_{IT} (N/mm^2)	E_{IT} (kN/mm^2)	d_h (μm)	d_v (μm)	$H_{V0.5}$	Porosity (%)
IIT 1	7065.0 $\pm$ 14	104.69 $\pm$ 20	37.30 $\pm$ 0.9	38.45 $\pm$ 0.8	646.35 $\pm$ 20	9 $\pm$ 1
IIT 2	3475.0 $\pm$ 21	82.02 $\pm$ 37	43.98 $\pm$ 2.5	44.05 $\pm$ 0.0	478.59 $\pm$ 13	12 $\pm$ 2
IIT 3	4846.0 $\pm$ 38	78.41 $\pm$ 52	39.44 $\pm$ 1.4	40.68 $\pm$ 0.9	577.76 $\pm$ 06	8 $\pm$ 1