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Mechanical and microstructural characterization of MCrAlY coatings produced by laser cladding: The influence of the Ni, Co and Al content

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ABSTRACT

Laser metal deposition (LMD) and laser cladding (LC) are alternative methods to thermal spraying processes to produce dense, high-quality coatings. In this work, two MCrAlY coatings (M = Ni + Co) have been prepared onto stainless steel substrate using a coaxial LC technique under two different Ni/Co and Al proportions. The mechanical properties were then evaluated with microhardness, nanoindentation, and three-point bending tests. The microstructure and composition of coatings were characterized by X-ray Diffraction (XRD) analysis and Field Emission Electron Microscopy (FESEM) coupled to an Energy Dispersive Spectroscopy (EDS) detector. The study revealed that the γ/β phases formed in the MCrAlY coating microstructure result in a lower elastic modulus than the austenitic stainless steel substrate, while an inverse behavior for hardness was observed due the presence of the aluminum-rich β-phase. Under flexural loads, the failure of coatings showed plasticity and anisotropy characteristics depending on the two laser tracks orientations evaluated.

1. Introduction

Aircraft and power-generation turbines are made from metallic components that are protected by thermal barrier coatings (TBCs). A TBC system is usually formed by a top ceramic layer [1,2] deposited onto a bond layer [3,4] over the substrate. The materials widely used for bond coatings are composed of MCrAlY superalloys (where M = Ni, Co, Fe or combinations of these). NiCoCrAlY and CoNiCrAlY are the most common superalloys used as bond coats [5] due to their good adhesion, optimal elastic modulus, high strength, and high-temperature oxidation resistance [6]. These MCrAlY alloys usually contain large amounts of Cr with small additions of Y, which hardens the solid solution. This solid solution effect of these elements blocks the dislocation movements through the grain boundaries, enhancing the common creep resistance of MCrAlY alloys [7]. Otherwise, an Al content between 8 and 15 wt% slows down crystal growth, resulting in a more thermally stable, adherent and continuous aluminum-rich oxide layer (α-Al_2O_3) [8,9]. Furthermore, it increases the amount of β-(Ni,Co)Al phase, which is harder than the gamma matrix phase in γ/β MCrAlY coatings [10].

Nowadays, the laser cladding process (LC) is gaining attention as an alternative technique to manufacture TBC coatings. Laser cladding can be applied as a rapid manufacturing technique consisting of the direct deposition of metallic alloys with high melting points, such as MCrAlY alloys. Specifically, coaxial laser cladding uses a special nozzle head to create a coniform annular gap, which encircles the focused laser beam with powder, melting the powder on the surface to be coated. The coaxial LC process has been tested to produce large, dense coatings by overlapping single laser tracks [11–17]. Even complex 3D pieces are able to be coated by LC using powder or solid wire as a material feedstock. In the same way, laser metal deposition (LMD) processes use this principle to deposit the material layer by layer in an innovative additive manufacturing process [18–20]. The continuous coatings obtained by these techniques are free of pores and cracks when the experimental conditions are well-controlled. These properties improve the resultant mechanical resistance and interfacial strength with the substrate. However, due to the brittle behavior of MCrAlY alloys at low temperatures [21], the experimental conditions must be well-studied and controlled in order to avoid residual stresses and material defects (pores, cracks, bonding defects, and others) [13,22]. Furthermore, several studies [23] have reported that the diffusion zone achieved between the coating and substrate is critical to optimize the resultant mechanical properties, it being desirable to reduce the chemical dilution of the coating to substrate. Moreover, the elastic modulus of the bond coat is also a critical mechanical parameter, since TBC systems are composed of several layers. The shear stresses expected between layers must be as low as possible to avoid delamination failures [5,6].

In this study, two MCrAlY coatings have been produced by the

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coaxial LC process. One coat was made with a higher concentration of Ni and Al, called NiCoCrAlY. The other was prepared with a higher concentration of Co, called CoNiCrAlY, for comparative purposes. After finding the best experimental conditions to form dense, continuous coatings using pre-alloyed powder as a feedstock material, an in-depth mechanical characterization was performed. In order to complete the study, the elastic modulus and hardness of the individual phases and of the whole coating were evaluated by nanoindentation [10,16,24,25]. Also, to analyze the strength and fracture mechanisms of the interface between layers, a three-point bending test was used [26,27]. Besides these techniques, other properties were investigated through measurements of microhardness and microstructural analysis by XRD, FESEM and EDS.

2. Experimental procedure

2.1. Materials and processing techniques

The feedstock materials used in this study were two commercial MCrAlY pre-alloyed powders supplied by Oerlikon Metco. A Ni-rich powder called NiCoCrAlY (Amdry 365-2) was mainly composed of (wt %) 47.1% Ni, 23% Co, 17% Cr, 12.5% Al and 0.4% Y. The mean particle size diameter was given by the supplier as 55 μm. In addition, a Co-rich powder called CoNiCrAlY (Amdry 995C) and composed of 38% Co with 32% Ni, 21% Cr, 8% Al and 0.45% Y was used to produce the second coating, with a mean particle size diameter of 65 μm. The substrate was a cold-rolled austenitic stainless steel sheet (AISI 304) with a thickness of 10 mm. Extensive coatings ($30 \times 30\ mm^2$) were obtained using a Nd:YAG solid state laser (Rofin-Sinar DY 022) in continuous mode and $\lambda = 1064$ nm. The laser power was programmed at 2.2 kW (maximum power). The diameter of the beam spot onto the substrate surface was 4 mm. The XYZ movement was achieved with a robotic-arm (ABB IRB 2400 unit) with 6 degrees of freedom. The scan velocity was set to 15 mm/s and the overlap ratio between tracks was programed to reach 40%. The powder was gas-assisted at a rate of 25 mg/mm using a coaxial annular nozzle (Precitec YC50) and a Sulzer Metco Twin 10-C powder feeder. Helium was used as a shielding and powder carrier gas, flowing at 20 l/min.

2.2. Coating characterization and microstructure

The microstructural characterization of the coating and substrate was analyzed on a cross- sectional view. Samples were cut and metallographically prepared using diamond abrasives of different grits. The compositional analysis was determined using a backscattered electron image detector (BSE) and energy dispersive spectroscopy (EDS) coupled inside a field emission scanning electron microscope (FESEM) (Zeiss ULTRA55). The crystalline characterization of the main phases was performed by X-ray diffraction (XRD) using a Philips X'pert diffractometer with monochromatic Cu-K_α radiation ($\lambda = 0.15406$ nm). The XRD patterns were obtained in the 2θ range from 20° to 90° and were subsequently analyzed using the X'Pert Plus software (PANalytical).

2.3. Mechanical tests

Three different tests were used for the mechanical characterization of the produced coatings and their individual phases and microstructures.

2.3.1. Microhardness measurements

Vickers hardness profiles from the coating surface to the substrate were evaluated in cross-sections by a microhardness tester (Shimadzu HMV-2, Japan) assisted by automatic measurement software. Three indentation arrays were replicated for each coating, spaced 100 μm apart. Results were subsequently averaged to obtain the microhardness profile for each coating. All tests were performed under a constant 980.7 mN load ($HV_{0.1}$) for 10 s, following the standard guidelines described by ASTM E384 [28].

2.3.2. Elastic modulus and nanohardness measurements

In order to obtain the elastic modulus and nanohardness of the whole coatings and main microstructural phases, a G-200 nanoindenter from Agilent Nanotech was used. Tests were performed under continuous stiffness measurement mode (CSM) in order to acquire the in-depth stiffness profiles. A matrix of 25 indentations was performed on the cross-section of each coating at a constant 2000 nm depth with displacement control, and the corresponding variation of force as a function of displacement was continuously recorded. From the measured data and following the method of *Oliver and Pharr* [29], the hardness H and the elasticity modulus E were calculated. Subsequently, the depth range used to calculate the characteristics of the single phases was evaluated through the observation and analysis of the acquired curves. In this way, we can ensure that the calculated hardness and elastic modulus values correspond to individual phases [4,30]. The Poisson's coefficient used for the Young's Modulus calculation was 0.3 for all tests.

2.3.3. Three-point bending test measurements

Three-point bending tests were performed on the coating-substrate system and in the substrate sample. A universal test machine (Shimadzu model AG-X, Japan) with a 50 kN load-cell and camcorder extensometry was used. The bending device was configured by three hardened steel rollers with 5 mm radius (Fig. 1). The distance between rollers was adjusted to 22 mm according to the thickness of the samples (coating + substrate). The deflection on the outer surface of the coating was measured during the test by an Epsilon Technology digital deflectometer, model 3540-004 M-ST. The movement of the punch during the test was simultaneously recorded. The speed was 0.50 mm/min at a constant displacement control.

The load versus displacement curve was recorded, as well as the load curve vs. central deflection at the coating surface (mm), and from these data the bending nominal stress ($\sigma_{flexion}$) and the strain (ε_{ext}) of the outer fiber (coating surface) were calculated using Eqs. (1) and (2), respectively.

$$\sigma_{flexion} = \frac{3 \cdot L \cdot F}{2 \cdot b \cdot t^2} \tag{1}$$

$$\varepsilon_{ext} = \frac{6 \cdot t \cdot d}{L^2} \tag{2}$$

where L is the distance between the lower rollers, F is the applied centered load, b is the sample width, t is the total thickness of the sample (substrate + coating) and d is the deflection measured at the centerline of the outer coating surface by the digital deflectometer. From the stress-strain curve, the flexural elastic modulus, the yield strength (0.2% of the deformation method), and the rupture stress (the

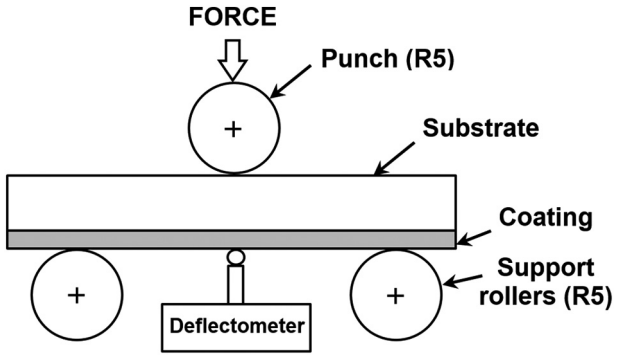

Fig. 1. Schematic of the three-point bending test configuration.