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Al/SiCp and Al11Si/SiCp coatings on AZ91 magnesium alloy by HVOF

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ABSTRACT

High velocity oxygen-fuel (HVOF) thermal spray has been used to fabricate Al, Al11Si and metal matrix composite (Al/SiCp and Al11Si/SiCp) coatings on the AZ91 Mg alloy. Taguchi design of experiment (DOE) methodology was used to analyze the influence of the HVOF spraying conditions (% SiCp in feedstock, spraying distance, number of layers and gun speed) in the main characteristics of the coatings (actual amount of reinforcement in the coating, porosity and thickness) and in some properties of the coatings such as hardness and adhesion. In general, for the same HVOF spraying conditions, the coatings fabricated using Al11Si as matrix presented higher thickness and lower incorporation of reinforcement, as well as higher hardness and adhesion values in comparison with those of pure Al matrix coatings. Independently of the matrix used, the % SiCp in feedstock and spraying distance seem to be the most important spraying parameters in controlling the properties of the sprayed coatings.

1. Introduction

Magnesium alloys are the lightest of all metals used as the basis for constructional alloys. This lightness, high strength to weight ratio and its demonstrated versatility makes this material a great choice in aerospace, transportation and in civil and military applications [1]. However, several drawbacks restrict the application of unprotected magnesium alloys, especially their low wear and corrosion resistance. The use of coatings is one of the most effective strategies to protect these light alloys against corrosion and wear. Among others, aluminum and aluminum composite coatings present a density which is only 1.5 that of magnesium and have high resistance to corrosion in many environments although they have limited wear resistance. As a consequence, the use of aluminum alloys and the addition of ceramic particles such as SiCp into the coatings are required to increase their mechanical behavior [2–7]. The aluminum matrix composite reinforced with ceramic particles allows obtaining simultaneously good wear and corrosion resistances, while low density of the substrate–coating system is maintained [8–12] and its coefficient of thermal expansion is reduced without deterioration of its thermal conductivity [13].

Different thermal spraying techniques have been used to deposit Al/SiCp coatings on magnesium alloys such as oxy-acetylene flame spray, cold spray and high velocity oxy-fuel (HVOF). Among the different spraying techniques, oxy-acetylene thermal spray is the simplest and cheapest one, therefore it is available even for small industries [14,15]. Its main limitation is the low kinetic energy of the sprayed material, which usually results in highly porous coatings. A reduction on porosity may be achieved by post-processing routes. Arrabal et al. [16] and Carboneras et al. [17] used oxy-acetylene flame spray to deposit Al/SiCp coating on different magnesium alloys and cold-pressing post-treatment was used to reduce the porosity of the coating up to values <0.5%. Cold spray is another alternative to deposit Al/SiCp coating on magnesium alloy, but some limitations are inherent to the technique. Due to the low temperature and the high velocity of the sprayed particles, there is a limited contact time between Al and SiC particles during the spraying process. These characteristics may cause the breaking of the ceramic reinforcement, as Leshchynsky et al. reported [18], which results in high porosity coatings and lower adhesion strength than that achieved with thermally sprayed coatings. This phenomenon increases as the reinforcement percentage does. These factors hinder in most cases the good mechanical properties of the coating in wear applications. HVOF combines the low heat input of the low pressure spraying technique with high kinetic energy of the sprayed powder, giving rise to low porosity coatings. This high energetic spraying technique has not been usually used on magnesium alloys because of their low melting point, although some successful examples can be found in the literature [19,20]. This processing technology is an interesting route to develop efficient corrosion and wear protective coatings over magnesium alloys, promoting its applications in the transport industry to reduce vehicle weight and fuel consumption.

In the present work, Al, Al11Si, Al/SiCp and Al11Si/SiCp HVOF coatings have been sprayed with the aim to determine the influence of the spraying parameters (spraying distance, number of deposited layers, volume fraction of reinforcement in the feedstock and gun speed) in the characteristics (thickness, actual volume fraction of the reinforcement and porosity) and mechanical properties (adhesion and hardness) of the sprayed coatings. In addition, the effect of the nature of the

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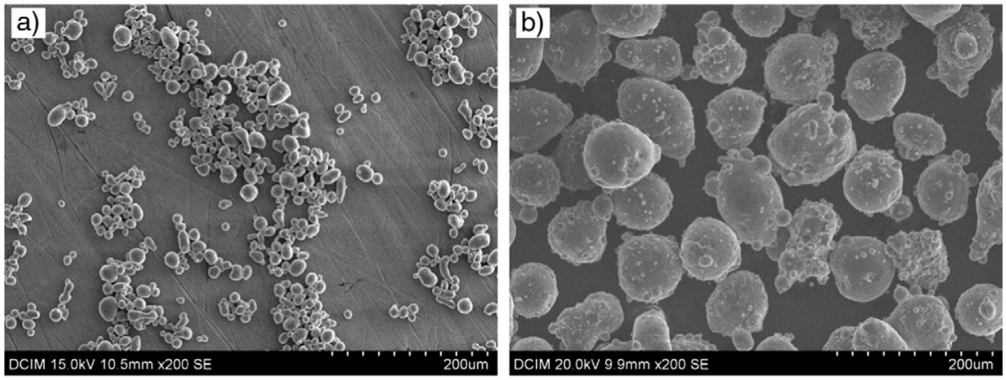

Fig. 1. SEM micrograph of (a) pure Al powders and (b) Al11Si powders.

matrix, i.e. Al and Al11Si, has been also evaluated. The relationship between the HVOF parameters and the characteristics and properties of the fabricated coatings has been analyzed by a Taguchi design of experiment (DOE) method.

2. Experimental procedure

2.1. Materials

AZ91 was supplied by Magnesium Elektron with the following nominal composition (in wt.%): 9 Al, 0.67 Zn, 0.23 Mn and balance Mg. The material was supplied in trapezoidal ingot of 7.5 kg and was cut into specimens of 30 mm × 25 mm × 3 mm for the HVOF process. All samples were sand blasted with corundum particle size of 1–3 mm, degreased with propanol and dried in warm air.

Pure aluminum powder was supplied by Flame Spray Technologies with an average size of 20 μm (Fig. 1a). The Al11Si powder was supplied by Sulzer with the following chemical composition (in wt.%): 0.01 Cu, 0.14 Fe, 0.01 Mn, 0.01 Mg, 11.4 Si, 0.01 Zn, 0.03 others and balance aluminum with an average size of 50 μm (Fig. 1b). Al/SiCp and Al11Si/SiCp composite coatings were obtained by using feedstock powder blends of Al and Al11Si powders with different proportions (0, 30 and 50 wt.%) of SiC particles (Navarro S.A.) with an average size of 26 μm. These powder blends were obtained in a rotational ball mixing with alumina balls after 1 h of mixing.

2.2. Spraying conditions

Al, Al11Si, Al/SiCp and Al11Si/SiCp coatings were fabricated using HVOF thermal spray equipment from Sulzer Metco (Unicoat, DS2600). The HVOF gun was placed on an anthropomorphic robot ABB IRB-2400/16 to control the spraying distance and the gun speed over the surface of the substrate. Oxygen and hydrogen were used as oxidizing and fuel gas, respectively. Proportions of both gases (635 NLPM – normalized liter per minute – for hydrogen and 214 NLPM for oxygen) and of air used as shielding gas (344 NLPM) were previously optimized to protect Al powder from oxidation and to reach supersonic flame. Nitrogen was used as transport gas to feed the powder into the gun.

To evaluate the influence of the HVOF parameters into the coating features and properties, a Taguchi DOE method has been used. Four factors (distance, wt.% SiCp in feedstock, number of layers in the coating and gun speed) with three levels (350, 450, 550 mm; 0, 30, 50% SiCp; 3, 6, 9 layers; 150, 200, 250 mm s^{-1} respectively) were selected. The factors and levels were used to design an orthogonal array L_9 (3^4) for experimentation. The nine Taguchi experiments for each of the two aluminum coating matrices are presented in Table 1.

To investigate the coating formation process single layer of the Al and Al11Si matrices was deposited on a F4000 grounded magnesium substrate by the so-called wipe test [21] using a spray gun transverse speed of 1500 mm s^{-1} at spraying distances of 350, 450 and 550 mm.

2.3. Specimen characterization

The cross-sections of the coated substrates were prepared by using a diamond disc cutter on hot conductive resin mounted samples, followed by grinding with SiC emery paper up to 1200 grit and polished with alumina suspension up to 0.5 μm. Thickness, porosity and actual reinforcement of the coatings were measured by means of an image analysis software (Image Pro Plus) on the captured images obtained by a light microscope (Leica DMR).

The adhesion strength of the coating to the substrate was evaluated by means of a PosiTest AT-Pull-Off Adhesion Tester following the ASTM D4541-02 procedure E standard [22].

Coating roughness measurements were performed by stylus profilemeter (SJ-210 Mitutoyo) with a resolution of 0.01 μm and according to DIN4776 specification [23].

Hardness tests were carried out on the cross-sections of the samples using a Vickers Buehler Micromet 2103 micro-hardness tester with a load of 500 g ($HV_{0.5}$). Averages of 10 tests for each coating were used to obtain representative values.

Table 1
Spraying condition for the different fabricated coatings according to Taguchi DOE method. Also given are the coating designations used throughout this paper.

Coating denomination				Spraying conditions		
Condition	Al	Al11Si	Distance (mm)	SiC in feedstock (vol.%)	Layers	Gun speed (mm s^{-1})
C1	Al-C1	Al11Si-C1	350	0	3	150
C2	Al-C2	Al11Si-C2	450	0	6	200
C3	Al-C3	Al11Si-C3	550	0	9	250
C4	Al/30SiC-C4	Al11Si/30SiC-C4	350	30	6	250
C5	Al/30SiC-C5	Al11Si/30SiC-C5	450	30	9	150
C6	Al/30SiC-C6	Al11Si/30SiC-C6	550	30	3	200
C7	Al/50SiC-C7	Al11Si/50SiC-C7	350	50	9	200
C8	Al/50SiC-C8	Al11Si/50SiC-C8	450	50	3	250
tC9	Al/50SiC-C9	Al11Si/50SiC-C9	550	50	6	150