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The Comparison of the Effect of Powder Morphology on the Microstructure and Mechanical Properties of WC-Co-Cr Coatings HVOF-Sprayed on Substrates Made of Alloy AZ31

Abstract: The paper presents results of comparative tests concerning the effect of the morphology and particle size of the WC-Co-Cr coating material on the microstructure and mechanical properties of coatings sprayed (using the high velocity oxy-fuel method (HVOF)) on substrates made of magnesium alloy AZ31. The tests involved the use of two types of commercial powders, i.e. agglomerated and sintered powder (AS) (Höganäs, Amperit 558.074) and sintered powder (S) (Höganäs, Amperit 554.071). The microstructures of the coatings were observed using digital light microscopy and scanning electron microscopy. The tests also involved the determination of porosity and roughness as well as measurements of instrumental hardness (H_{IT}) and Young's modulus (E_{IT}). The microscopic observations revealed that the coatings were characterized by the relatively compact, dense and uniform structure as well as good adhesion to the substrate. The porosity of the S-type coating was approximately 1.5 times higher than that of the AS-type coating. In addition, the S-type coating was visibly thinner (than the AS-type coating), which could be ascribed to a lower powder feed rate applied during the spraying process. The surface of the AS-type coating was characterized by lower roughness (R_a = 4.5 ± 0.1 μm) than that of the S-type coating (R_a = 5.8 ± 0.3 μm). The differences in terms of instrumental hardness (H_{IT}) and instrumental Young's modulus (E_{IT}) were also small. However, it could be noticed that the more compact structure and lower porosity of the AS-type coating resulted in the obtainment of slightly higher values of both H_{IT} and E_{IT}.

Keywords: WC-Co-Cr coating, HVOF spraying, magnesium alloy AZ31, powder morphology, microstructure, mechanical properties

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Introduction

Magnesium alloys belong to a group of materials, which enjoy increasingly high popularity with researchers. Some of the most favourable properties of the aforesaid materials include low specific gravity (1.74 g/cm^3) and high specific strength [1–3]. Because of their properties, magnesium alloys are applicable in the automotive, aviation, chemical, shipbuilding, electronic and many other industries [4]. However, the use of magnesium alloys is also limited by their low resistance to corrosion, erosion and abrasion as well as low hardness [5–7]. The above-presented problems could be solved by the deposition of protecting coatings on surfaces of materials made of magnesium alloys. Regrettably, also the applicability of the aforesaid solution is restricted by the high flammability and plasticity of magnesium alloys [8, 9]. For this reason, among many thermal spraying methods it is necessary to select a technique enabling the deposition of a dense and well adhesive coating under conditions of relatively low temperature affecting the substrate [10–12]. The above-named conditions are satisfied by the HVOF spraying method (*High Velocity Oxy-Fuel*). In addition, the HVOF method can be successfully used to deposit coatings made of hard materials resistant to intense abrasion and corrosion. The aforesaid coatings are also characterised by favourable adhesion and low porosity [13–17]. Taking into account the plastic nature of substrate and the hard nature of the coating as well as the significant improvement of primary mechanical and functional properties of the coating, materials selected for the research-related tests were cermets based on tungsten carbide [18–21]. It should be noted that the HVOF technique is the primary method used to obtain cerametallic coatings [22, 23]. In addition to process parameters, key technological factors include the condition and size of powder particles [24, 25].

Available reference publications contain little information concerning the deposition of protective coatings thermally sprayed on base materials made of magnesium alloys [26, 27]. The authors' individual studies constitute an attempt to fill this gap in research publications [28–30].

The tests discussed in the article aimed to compare the effect of the size of powder particles and powder morphology on the microstructure and primary mechanical properties of WC-Co-Cr cerametallic coatings deposited (using the HVOF method) on the substrate made of magnesium alloy AZ31.

Test materials and methods

The coatings were deposited using a JP-5000 HVOF spray gun (TAFA). The substrate was made of 5 mm thick magnesium alloy AZ31. The surface of specimens was previously subjected to abrasive blasting. The aforesaid surface processing method aimed at surface cleaning and expansion. The coating material was cerametallic powder based on tungsten carbide, on the matrix of cobalt with an addition of chromium WC-10Co-4Cr (% by weight). The tests involved two types of commercial powders, i.e. agglomerated and sintered powder (AS) (Höganäs, Amperit 558.074) and sintered powder (S) (Höganäs, Amperit 554.071). The size and the average size of powder particles are presented in Table 1. The powder particles are presented in Figure 1.

Table 1. Comparison of the size and average size of test powder particles

Powder type	Size range, μm	Average particle size, μm
AS	15 – 45	d_{50} = 32
S	5 – 25	d_{50} = 17

The primary process parameters are presented in Table 2. Differences in coating deposition process parameters resulted from various sizes of powder particles (selected on the basis of individual preliminary tests) [32, 33].

The roughness of the surfaces formed during the spraying of the coatings was measured in

Table 2. Designation of specimens and spraying process parameters

Specimen designation	Fuel flow rate l/h	Oxygen flow rate l/min	Powder feed rate g/min	Spraying distance mm
AS	26	800	70	360
S	16	600	30	280

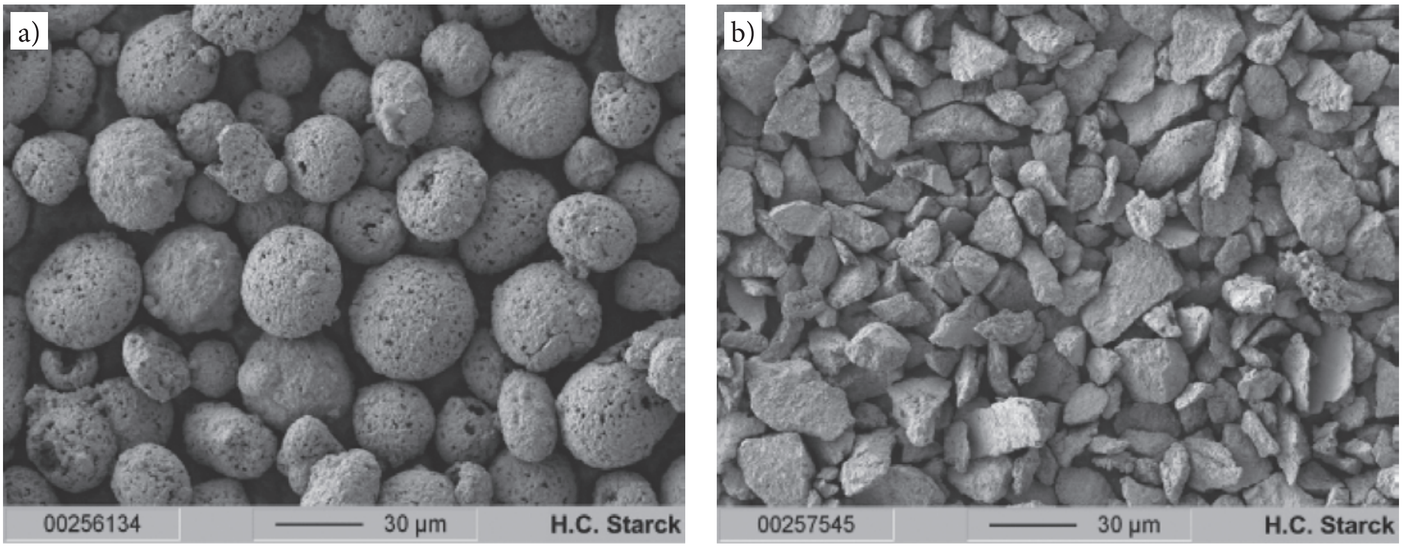

Fig. 1. Coating materials in the as-received state: a) powder AS and b) powder S [31]

accordance with the ISO 4288 standard, by identifying parameter R_a (arithmetic average of absolute values of ordinates in the roughness sampling cut-off). The measurements (involving 10 repetitions) were performed using a Mahr Surf PS 10 contact profilometer. To observe the microstructure of the coatings, the specimens were cut across to sample specimens which were subsequently included in resin and subjected to metallographic preparation using SiC paper and diamond slurry having a grain size of 3 µm. The subsequent stage involved observation performed using a VHX6000 digital light microscope (Kyence) and a scanning electron microscope. The porosity of the coatings was determined in accordance with the ASTM E2109-01 standard. The computer-aided image analysis was performed using the ImageJ software programme. The values of porosity were calculated on the basis of 20 photographs obtained using a magnification of 500x. Hardness instrumented indentation was determined in accordance with the ISO 14577-4 standard using an NHT[3] hardness tester (Anton Paar). The indenter used in the tests was characterised by Berkovich geometry; the maximum force amounted to 500 mN. The measurements were performed in accordance with methodology described by Oliver and Pharr [34]. In turn, the value of Young's elastic modulus by instrumented indentation was identified in accordance with the methodology described in publication [35]. To determine the value of the aforesaid modulus, the value of maximum force changed within the range of 50 mN to 500 mN (at a step of 50 mN). The value of the parameter describing brittle crack resistance K_C was identified using the Vickers indenter and measurements of lengths of cracks formed in the corners of the indentation (Fig. 2) [36].

The test involved the making of 15 indentations (involving the cross-section of the specimen), the performance of measurements of characteristic dimensions and the substitution of the latter in the formula proposed by Wilshaw and Evans [37]:

$$K_C = 0.079\left(\frac{p}{a^{3/2}}\right)\log\left(\frac{4.5a}{c}\right) \tag{1}$$

where
P – value of maximum force N (amounting to 9.81 N)
a – half of the Vickers indentation diagonal, m
c – crack length from the centre of the indentation, m

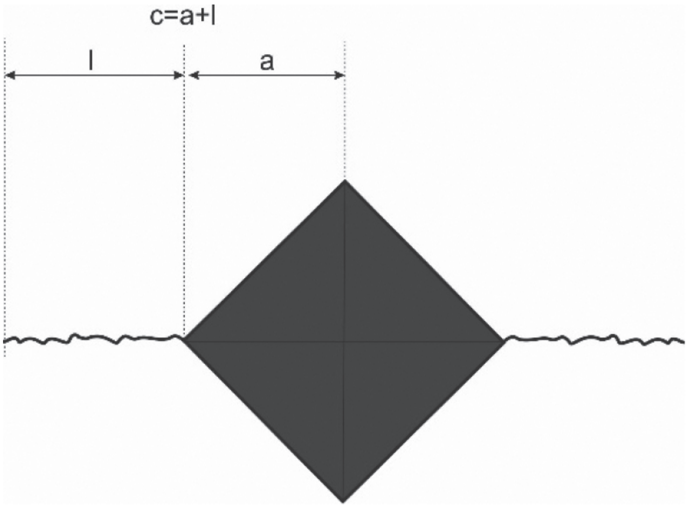

Fig. 2. Schematic diagram of Vickers indentation with cracks formed in the test

Test results

The microstructure of the sprayed coatings is presented in Figure 3. As can be seen, the coatings are characterised by the relatively dense, compact and uniform structure as well as good adhesion to the substrate. All substrate surface irregularities were filled by the coating material very well. The area of contact between the coating and the substrate was characterised by the proper mechanical seizure of the particles, which indicated the high adhesion of the coatings. The above-presented structure was consistent with related reference data [18, 38, 39]. Because of the significantly lower feed rate of the powder (Table. 2), the S-type coatings were visibly thinner than the AS-type coatings; the thickness of the coating being 100 μm and 200 μm respectively. Both coating types were deposited using the same number of spray pistol runs.

The coating surface was relatively smooth. The slightly lower value of surface roughness identified in specimen AS resulted from the fact that powder particles of spherical morphology tend to form more regular splats and lamellas in comparison with powder particles characterised by irregular shapes [40]. The surface porosity and roughness values are presented in Table 3. The results obtained in the tests were similar to those presented in related reference publications [41, 42].

Table 3. Comparison of the roughness and the porosity of the coating surface

Specimen designation	Surface roughness R_a, μm	Porosity, % by volume
AS	4.5 ± 0.1	2.9 ± 0.7
S	5.8 ± 0.3	4.8 ± 0.9

The average values of hardness instrumented indentation H_{IT} and those of Young's elastic

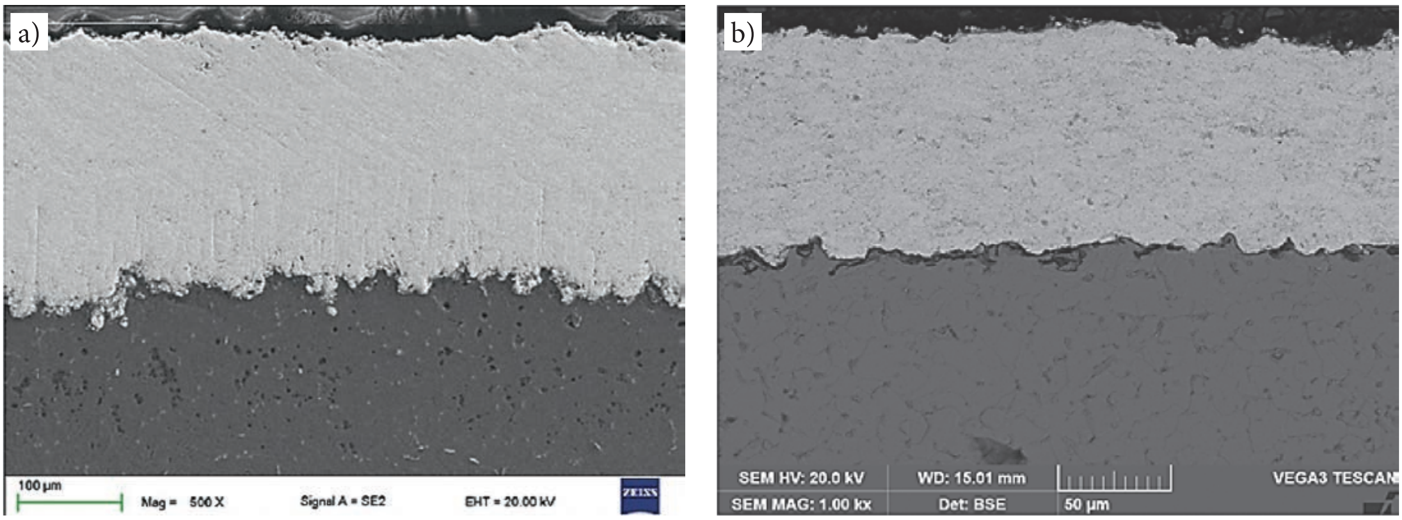

Fig. 3. Cross-section of the coatings: a) specimen AS and b) specimen S

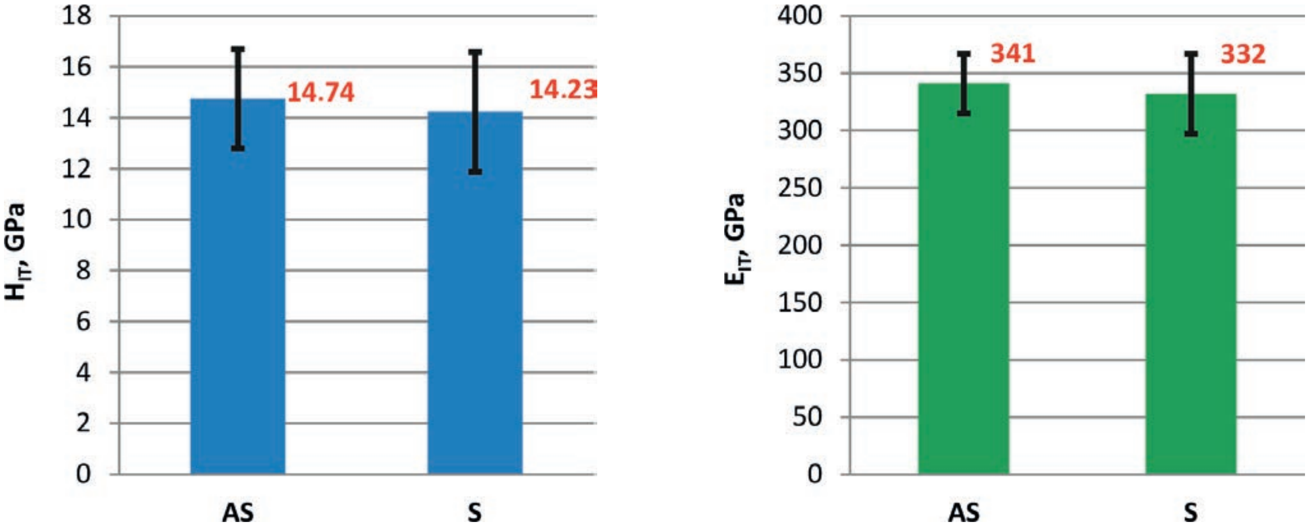

Fig. 4. Comparison of average values of H_{IT} and E_{IT}

modulus by instrumented indentation E_{IT} are presented in Figure 4. As can be seen, the differences are only slight, yet the more compact structure and the lower porosity of the AS-type coatings translated into slightly higher values of both H_{IT} and E_{IT}. The hardness values obtained in the tests were very similar to those contained in reference publications [18, 43]. However, the values of E_{IT} were slightly higher than those found in reference publications [44, 45]. The foregoing was probably caused by a different indenter type and the appropriate adjustment of corrective factors [46].

The values of parameter K_C, representing brittle crack resistance, are presented in Table 4. As can be seen, specimen AS was characterised by higher brittle crack resistance, which resulted from better cohesion between the lamellas and the more compact structure [47]. However, the higher porosity of specimen S could prevent or, at least, slow down the propagation of cracks; an important aspect being the size of pores (usually not exceeding several micrometres) [39]. It should be noted that the results obtained in the tests correlated with related data contained in reference publications [48, 49].

Conclusions

The above-presented tests aimed to identify the effect of the morphology and size of the WC-10Co-4Cr powder particles on the microstructure and mechanical properties of HVOF-sprayed coatings. The analysis of the test results justified the formulation of the following conclusions:

- proper adjustment of process parameters enabled the obtainment of high-quality cermetallic coatings on the substrate made of magnesium alloy AZ31,
- morphology of powder particles significantly affected the structure of the coating and its mechanical properties,
- size of powder particles did not affect mechanical properties; each type of powder was sprayed using a separate set of previously adjusted spraying parameters,
- spherical morphology of the agglomerated and sintered powder translated into higher process efficiency.

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