MECHANICAL PROPERTIES OF PLASMA SPRAYED LAYERS OF NiAl10 AND NiAl40 ON AZ91 ALLOY

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Abstract

In this work, plasma coatings of NiAl10 and NiAl40 on magnesium alloy AZ91 substrate were prepared by the hybrid plasma spraying system WSP®-H 500. The both plasma sprayed coatings of NiAl10 and NiAl40 have metallurgical bond. The thicknesses of microstructures in the cross-section of NiAl10 and NiAl40 plasma sprayed coatings prepared by 9 passes were 374 and 440 μm respectively. Adhesion test of plasma sprayed layers was performed using a modified ASTM C 633 standard. The tensile adhesion strength values are 24.7 MPa for NiAl10 coatings and 12.3 MPa for NiAl40 coatings. Abrasion resistance according to Slurry Abrasion Response (SAR) test of NiAl40 layers had similar values (0.12 g/cm^2)in a comparison with the uncoated AZ91 (0.126 g/cm^2). Layers NiAl10 had greater weight losses (0.175 g/cm^2) than uncoated AZ91. Microhardness of plasma coating of NiAl40 is several times greater than microhardnesses of plasma coating of NiAl10 and uncoated substrate AZ91.

Keywords: Plasma spraying, nickel alloys, adhesion strength, wear resistance

1. INTRODUCTION

Magnesium alloys belong to promising materials for light-weight applications in automotive and aerospace industries due to their high specific strength and stiffness [1]. Nevertheless, low corrosion resistance of magnesium and its alloys considerably limits theirs possible applications. Magnesium alloys are well known to undergo galvanic corrosion, which often results in serious pitting corrosion damage [2]. To solve this problem, magnesium and its alloys can be protected by surface layers that are more resistant to environment. From scientific publications, it is well known that there are many works focusing on the research of plasma sprayed metals coatings especially on magnesium and magnesium alloys [3]. Intermetallic Ni-Al based compounds belong to promising candidates as materials for high temperature applications [4] and also as protective layers due to their excellent combination of properties such as resistance to oxidation up to 1573 K, high thermal conductivity and high hardness while maintaining low density of 5.86 g·cm^{-3} [4, 5]. However, the Ni-Al intermetallics are fragile and have low ductility at low temperatures, which may increase resistance to wear [6].Therefore, a lot of effort has been focused since now on preparation of Ni-Al based layers. The Ni-Al based protective layers are widely used in industry as bond-coats for thermal barrier coatings (TBC) [6, 7], but they are also used as top-coats which particularly improve resistance to abrasive wear, due to their high hardness [8]. In this work, plasma coatings of NiAl0 and NiAl40 alloys were prepared using the hybrid plasma spraying system WSP®-H 500. Prepared layers were observed by using the electron scanning microscope (SEM). Essential mechanical properties of the coatings, such as adhesive strength, microhardness and wear resistance were assessed.

2. EXPERIMENTAL PART

The NiAl10 and NiAl40 (wt.%) powders (both obtained from Foundry Mníšek p.B., Czech Republic) with powder particles diameter of 125 ± 45 μm and 315 ± 180 μm, respectively, were used as feedstock materials. Plasma coatings were prepared by means of a hybrid water-stabilised plasma torch WSP®-H 500 with power up to 160 kW (processing parameters are shown in **Table 1**). The powder was injected into the plasma jet by a carrier gas consisting of Ar and of H_2 (7 vol.%). Spraying distance of 350 mm was experimentally determined as distance where the powder was completely melted throughout, but it is not overheated or oxidized. In present work, the Ni-Al layers were prepared with nine passes over the substrate preheated to 250 ± 20 °C. Each pass represents one pass of plasma burner over the substrate by a robot moving with the speed of 300 mm/s. Substrates with the dimensions of 70x20x5 mm^3 were made from the AZ91 magnesium alloy (as-cast state), while its surface was grounded with an abrasive paper P-700 and degreased with acetone. Further, the plasma coated samples were cut into specimens for microstructure observations by a scanning electron microscope Carl Zeiss SMT, EVO MA15. The microstructures of plasma sprayed coatings in cross-section were mapped in the image analysis program (ImageJ) and the area fraction of porosity was calculated using the program.

Table 1 Plasma spraying parameters

Spraying parameters	NiAl10, NiAl40
Rate of powder feeding NiAl10 ($g \cdot min^{-1}$)	120
Rate of powder feeding NiAl40 ($g \cdot min^{-1}$)	50
Temperature of preheated substrate	250 ± 20 °C
Spraying distance (mm)	350

The Tensile Adhesion Tests (TAT) were performed using a modified ASTM C 633 standard. The cylindrical samples with diameter of 20 mm were machined from commercial magnesium alloy AZ91. Thickness of the deposited coatings was at least 350 µm in order to avoid penetration of the glue to the substrate. Low-carbon steel counterparts, adhesive epoxy glue and universal tensile tester Instron 1362 (UK) were used for evaluation of the sprayed coatings adhesion/cohesion strength which was determined as average value of at least two adhesion tests. Wear resistance of the samples was evaluated by Slurry Abrasion Response (SAR) test using the ASTM standard and force of 22 N applied at each sample [9]. The tests were performed in four increments (runs) with mass loss being measured after each run. After each run the specimens were ultrasonically cleaned, dried and weighted. The suspension used as abrasive medium consisted of 150 g of organic oil and of 150 g of alumina powder having average powder particles size ranging from 40 to 50 µm. It should be noted that the accuracy of the measurement reaches typically ± 5 % [9]. Microhardness was measured using Hanemann microhardness tester (Zeiss, Germany) equipped with Vickers indenter mounted on the optical microscope with fixed load of 1 N.

3. RESULTS AND DISCUSSION

3.1. Microstructure

The SEM micrographs displaying the morphology of the NiAl10 and NiAl40 powders used as feedstock for the plasma spraying are shown in **Figure 1**. Particles of the NiAl10 powder were mostly irregular showing traces of circular or rather elliptic shapes with rough surface. On the other hand, the NiAl40 powder contained irregular particles with smooth surface.

The SEM micrographs showing the morphology of the prepared coatings made from NiAl10 and NiAl40 are shown in **Figure 2**. One can see that the surfaces were characterized by high porosity and by presence of classic splats mainly irregular in shape. The NiAl10 coating contained aluminium oxides, which manifested themselves as dark splats. The NiAl40 coating, which was made from much coarser powder particles, contained larger splats and also some sharp-edged particles that were only partially melted as is clearly visible in **Figure 2**. The cross-section microstructures of NiAl10 and NiAl40 plasma coatings prepared by nine passes of plasma torch over the AZ91 substrate are shown in **Figures 3** and **4**. Present plasma coatings were inhomogeneous with certain porosity and contained splats, not melted rounded particles and splats made from oxides. The average plasma coating thickness for each used materials are shown in **Table 2**.

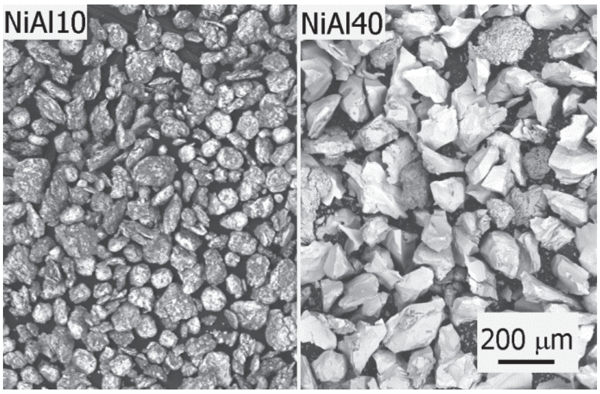

Figure 1 Feedstock powders, NiAl10, Fraction - 25 +45 μm, NiAl40, Fraction - 180 +100 μm

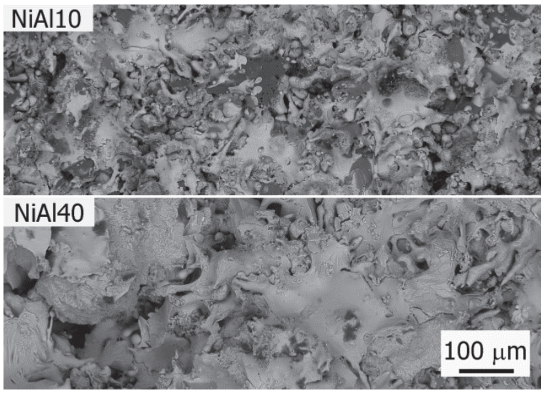

Figure 2 Free-surface of the NiAl10 and NiAl40 coating

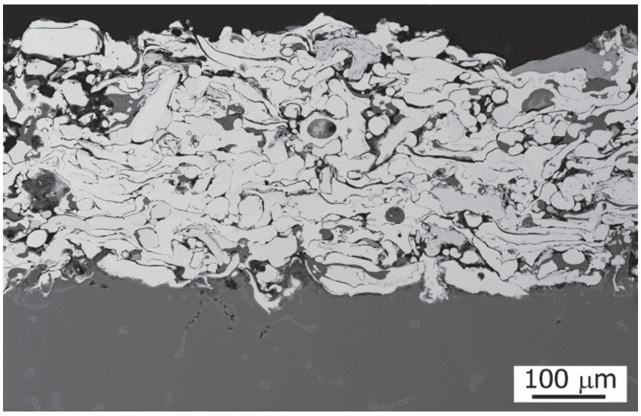

Figure 3 Microstructure on the cross-section of the NiAl10 plasma coating on magnesium alloy after 9 passes

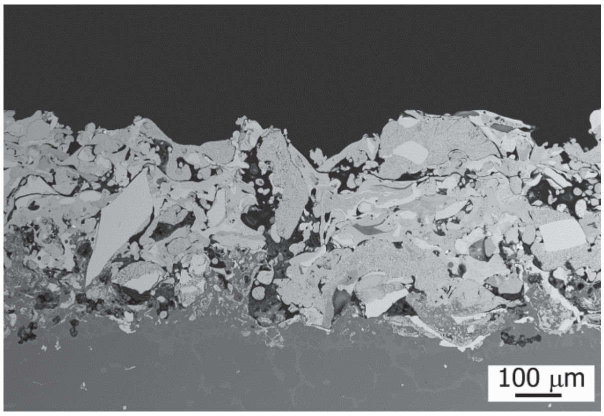

Figure 4 Microstructure on the cross-section of the NiAl40 plasma coating on magnesium alloy after 9 passes

Table 2 The average thickness of plasma sprayed coatings made from NiAl10 and NiAl40 with average values of porosity

Material	thickness (μm)	area porosity (%)
NiAl10	374 ± 26	21.6 ± 3.8
NiAl40	440 ± 48	17.1 ± 2.5

3.2. Adhesion strength of prepared coatings

The tensile adhesion strength values for the NiAl10 and NiAl40 coatings sprayed on at 250 ± 20 °C preheated magnesium alloy were 24.7 ± 0.5 MPa and 12.3 ± 0.94 MPa, respectively. The adhesion strength results of the NiAl10 coating were comparable to the values published by Parco et al. [10] who studied the influence of chosen preparation conditions of the AZ91 alloy substrate on adhesion strength of plasma coatings made of Al, $NiAl_5$ and Al_2O_3. They observed significant difference of the adhesion strength of prepared NiAl5 coats regarding the previous preheating the AZ91 alloy. It was clearly shown, that the polished and preheated alloy at 160 °C reached adhesion strength of 25 MPa, a value similar to that observed in our case, while without preheating it reduces only to 17 MPa [6]. The fracture surfaces of both the prepared plasma coatings after the

TAT tests were observed by the electron scanning microscopy as is shown in **Figures 5, 6**. The morphology of the NiAl10 plasma coating with detail of the fracture surface is shown in **Figure 5**. Places, where the NiAl10 coating ruptured (cohesive damage of splats) showing individual splats are marked with arrow. Additionally, the NiAl40 plasma coating showed as well poor adhesion to the substrate as can be observed in **Figure 6**. The fracture surface contained original grinding surface of the AZ91 substrate which lacks any evidence of partial melting (pointed with arrow). More importantly, evidences of brittle fracture across the splats are shown and pointed with arrows. These findings can explain why the value of adhesive strength of plasma sprayed NiAl40 coating was half the adhesive strength of plasma sprayed NiAl10 coating.

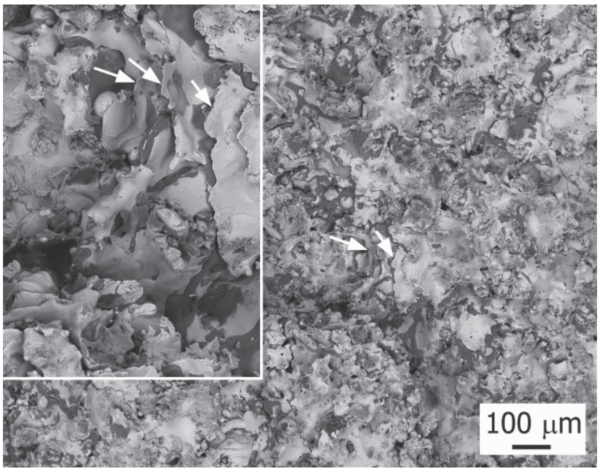

Figure 5 Microstructure of the NiAl10 plasma sprayed coating after TAT test

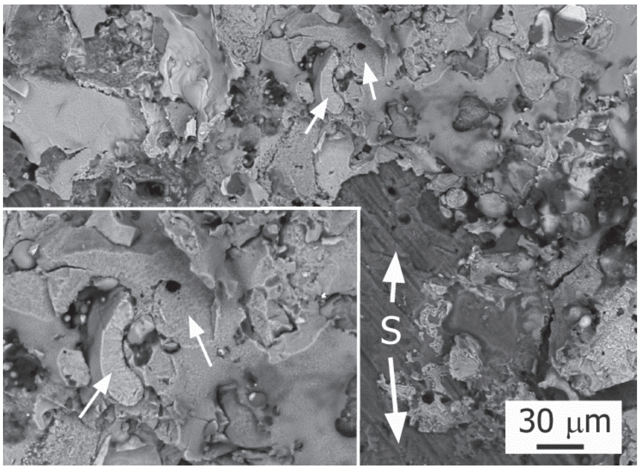

Figure 6 Microstructure of the NiAl40 plasma sprayed coating after TAT test

3.3. Wear resistance

The results of the wear resistance measurements, namely the dependence of mass losses on path lengths of 576, 1152, 1728 and 2304 m, are shown in **Figure 7**. Present results show that weight losses are linear for both the investigated plasma sprayed coatings as well as for uncoated AZ91. Weight losses are greater in case of plasma coating of NiAl10 0.52 g·cm^{-2}, compared with uncoated AZ91 0.30 g·cm^{-2}, and also with plasma coating of NiAl40 0.36 g·cm^{-2}. The test conditions are relatively aggressive and the substrate material bulk has favourable pore-free and homogeneous microstructure. This is the cause of its best result.

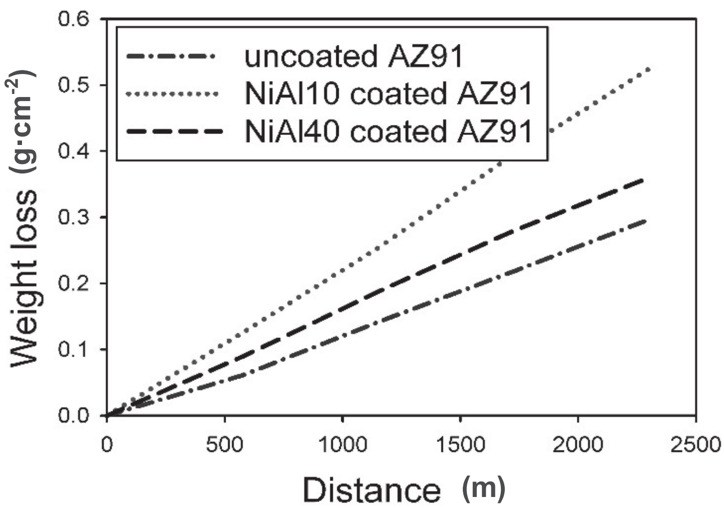

Figure 7 The SAR test results displaying the weight loss depending on wear distance

After the SAR tests, the microstructure of the samples was observed by an electron scanning microscope as is shown in **Figure 8**. One can see that microstructure of the uncoated AZ91 alloy contained intermetallic $Al_{12}Mg_{17}$ phases which influence on the wear resistance is negligible.

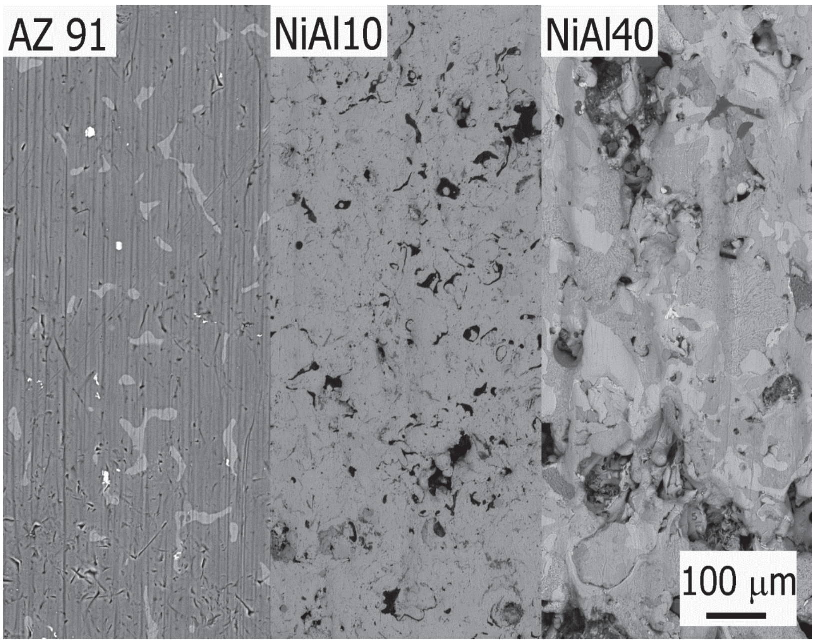

Figure 8 Free-surface of samples after measurement of abrasion resistance showing the uncoated AZ91 alloy and plasma sprayed NiAl10 and NiAl40 coatings

More importantly, the surface contained long parallel scratches over the entire surface area. In comparison, the surfaces of plasma coatings made of NiAl10 and NiAl40 were porous which increased the total weight loss during the SAR test. The plasma sprayed NiAl40 coating showed presence of heterogeneous structures with presence of different Ni-Al based intermetallic phases. However, regarding the previous results, no traces of tearing the individual splats or whole parts of the coating suggesting consistent abrasion throughout the entire plasma sprayed coatings was observed (see **Figure 8**).

3.4. Microhardness

The microhardness of prepared samples was measured on the metallographical cross sections throughout the entire layer and its average values are shown in **Table 3**. The highest average hardness of plasma sprayed NiAl10 coating was 149 HVm, which is similar to the value published by Hsiao [11] who prepared NiAl5 plasma coatings with hardness in the range of 160 - 210 HV300. On the other hand, the plasma sprayed NiAl40 coating showed presence of two different intermetallic phases which presence resulted in ultra-high hardness varying between 495 and 947 HVm. Microhardness of plasma coating of NiAl40 was several times higher than the of NiAl10 coating. Nevertheless, such ultra-high hardness did not improve the wear resistance mainly due to the presence higher porosity of the NiAl40 coating.

Table 3 Microhardness of the plasma-sprayed coatings and of uncoated AZ91 alloy

Sample	HVm
uncoated AZ91	120 ± 42
NiAl10 coating	149 ± 31
NiAl40 coating	495 ± 146 / 947 ± 156

4. CONCLUSIONS

In this work, plasma sprayed coatings of NiAl10 and NiAl40 were prepared on magnesium alloy AZ91 by hybrid water-stabilized plasma torch WSP®-H 500. The plasma sprayed coatings of NiAl10 is very inhomogeneous formed by metal and Al_2O_3 splats, unmelted spherical particles. The plasma sprayed coatings of NiAl40 contains spherical particles, splats with different content of nickel and aluminium and Al_2O_3 splats. The tensile adhesion strength values are 24.7 MPa for NiAl10 coatings and 12.3 MPa for NiAl40 coatings. In the case of plasma coatings NiAl10 there is a cohesive damage of layers and individual splats peel off. In the case of plasma coatings NiAl40 an adhesion layer damage is observed, and brittle fracture across splats as well. The test of abrasion resistance have shown that NiAl40 layers have similar values 0.120 g/cm^2 in compared to uncoated AZ91 0.126 g/cm^2. Layers NiAl10 have value of weight losses 0.175 g/cm^2. Microhardness of plasma coating of NiAl40 is 495 /947 HVm for a bimodal structure and microhardness of plasma coating of NiAl10 have values of 149 HVm and compare well with uncoated substrate AZ91 120 HVm.

ACKNOWLEDGEMENTS

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