Characteristics of Cold Spray Aluminium Coating on ZE41A-T5 Magnesium, AA7075 Aluminium Alloys and 4130 Steel Substrates

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ABSTRACT

Cold spray is a recent development by which a high-rate deposition process of small particles in solid state are mixed with heated gas and accelerated to supersonic velocities through a nozzle. The particles impact the target surface with sufficient kinetic energy to cause plastic deformation and consolidation with the substrate material to bond together, rapidly building up a layer of deposited material. This process uses high velocity rather than high temperature to produce coatings, and thereby minimize many disadvantages of high temperature reactions, which are characteristics of typical thermal sprayed coatings. The ease of initiation of deposition depends critically upon substrate type. Hence, this research was carried out to characterize the substrate materials and investigate the possible bonding mechanism at the interface.

Aluminium powder of 99.9 wt. % purity has been sprayed by using cold spray method onto a range of substrates; which are ZE41A-T5 magnesium alloy, AA7075 aluminium alloy and 4130 steel. The chemical composition of the coating and interface was examined by using Scanning Electron Microscope (SEM) and Energi Dispersive X-Ray (EDX) analysis. Microhardness testing was conducted to vertically trace the hardness profile around the interface.

It was observed that 1 – 2 µm thickness of Al_2O_3 *layer formed at the interface of all samples, which due to the reaction of aluminium particles with oxygen. The aluminium cold spray coating on the ZE41A-T5 magnesium substrate has the highest hardness and the lowest porosity percentage. The possible mechanism of bonding is mechanical interlocking, which is supported by the evidence that the interface at the entire samples is rather curvature than a straight.*

Key words: aluminium cold spray coating, kinetic energy, plastic deformation, porosity, mechanical interlocking

Introduction

Cold spray processing is a high-rate deposition process (at velocity 50 – 1000 m/s) in which small particles in solid state are mixed with heated gas and accelerated to supersonic velocities through a nozzle. The particles impact the target surface with sufficient kinetic energy to cause plastic deformation and consolidation with the substrate material to bond together, rapidly building up a layer of deposited material. This process uses high velocity rather than high temperature to produce coatings. The combination of high temperature and velocity will causing deformation of the particle droplets. Upon impact, the droplet will undergo rapid solidification forming a spalt due to continuous impact process. This will lead to thickness build up and forming of lamellar structure[1].

Bonding of the coating to the substrate and cohesion between consecutive splats is influenced by residual stresses within the coating, melting and localized alloying at the contact surfaces between particles and substrates, diffusion of elemental species across spalt boundaries, atomic-level attractive forces and mechanical interlocking between the coating and the substrate[2].

This research investigated characteristics of aluminium clod spray coating on different substrate, they are 4130 Steel, ZE41A-T5 Magnesium and AA7975 Aluminium Alloy

Experimental Method

Aluminium powder of 99.9 wt. % purity has been sprayed by using cold spray method onto three types of substrates; which are ZE41A-T5 magnesium alloy, AA7075 aluminium alloy and 4130 steel. Standard metallography preparation was done for each sample, which includes grinding, polishing using 0.05µ Al_2O_3 paste, and etching. Etchants for ZE41A-T5 magnesium alloy and AA7075 aluminium alloy samples are 5 % HF, while for 4130 steel samples are 2% Nital. for the 4130steel substrate and 5% HF for the Aluminium coating. The coating and interface chemical composition were examined using scanning electron microscope (SEM) and energi dispersive X-Ray analysis (EDX). In order to investigate the mechanical properties of the coating, interface and substrate area, microhardness test were conducted in *Mitsuzawa microhardness tester*. Vertical traces of microhardness measured and averaged the values at the same depth relative to the interface.

Results and Discussion

Aluminium Cold Spray Coating on ZE41A-T5 Magnesium Alloy

Microstructure of the aluminium coating, interface and substrate was available in Fig. 1, in which it is clear that that the coating particles are tightly bonded to the substrate and have very low percentages of porosity. This may indicates good quality of adhesion, and confirmed by more detailed micrograph in Fig. 2.

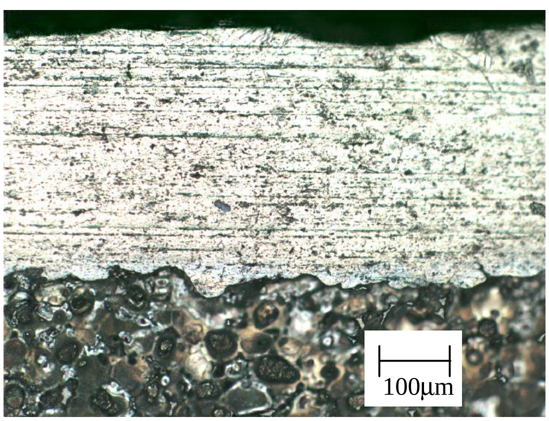

Fig. 1. Cold sprayed aluminium coating on ZE41A-T5 magnesium alloy substrates.

Table 1. Microanalysis of cold sprayed aluminium coating on ZE41A-T5 magnesium substrate on positions shown in Fig.2

Positions		Chemical Composition, wt.%						
		C	O	Al	Zn	Si	Ce	Mg
Coating	1	-	7.21	rem	-	-	-	-
	2	3.72	4.11	rem	0.68	1.17	-	-
	3	3.58	5.25	rem	1.1	1.11	-	-
Interface	4	2.82	32.1	24.9	1.62	1.05	-	32.1
Substrate	5	4.93	14.6	3.42	2.72	0.21	-	rem
	6	1.64	6.12	1.83	31.5	-	1.63	rem
	7	3.22	8.18	3.39	0.86	-	-	rem

Table 1 lists that the aluminium content at all positions in the coating is higher than 90 wt. %, although positions 2 and 3 show the presence of Zn and Si impurities with the amount of 0.86 – 1.83 wt. %. This may confirm that the coating material is pure aluminium powder. The Zn and Si impurities may come from the nozzle gun, which made of steel.

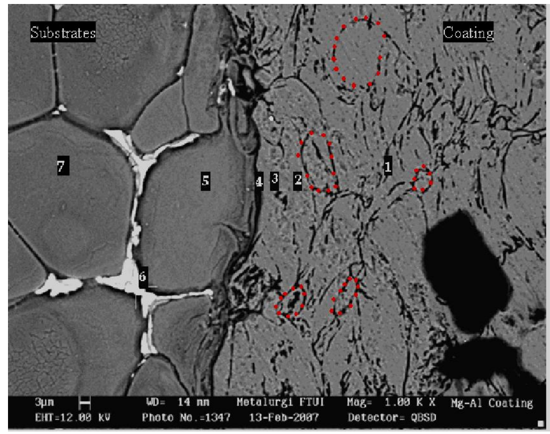

Fig. 2. SEM micrograph (back-scattering mode) of the interface of aluminium cold spray coating on ZE41A-T5 magnesium alloy. Areas that were examined are labeled (1), (2), (3), (4), (5), (6) and (7), and the results are presented in Table 1.

The SEM micrograph (Fig. 2) shows the presence of dark layer with thickness of ~1µm along the interface. Referring to EDX analysis at position 4 (see Table 1), the interface shows high oxygen content of 32.1 wt. %. Hence, it indicates formation of Al_2O_3 due to the reaction of Al particle with oxygen. The fraction of Al:O = 24.9:32.1 at position 4, is equal to 1:2. It may not exact to 2:3 fractions which probably due to the analytical SEM probe have bigger size than the layer which is only 1µm.

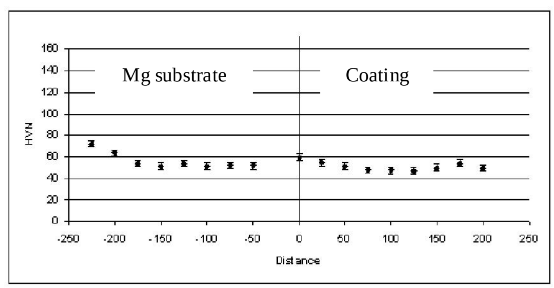

Fig. 3. Vickers microhardness profile of the aluminium cold spray coating on ZE41A-T5 magnesium alloy substrate, started from the substrate.

Fig. 3 shows the average hardness of aluminium coating on the ZE41A-T5 magnesium substrate is 50 HVN. It is much higher than the hardness of pure aluminium from literature which is 15 HVN. This possibly indicates that the aluminium particles exhibited strain hardening upon impact, increasing the density of dislocations within the grains and therefore, the hardness of the coating. This can be explained by the fact that the coating has elongated grains (see Fig. 2), with grain diameter ratio of 5:2.

The presence of Al_2O_3 layer is also supported with the high hardness of the interface of 60 HVN. Although the hardness of Al_2O_3 from the literature is significantly higher (hardness of Al_2O_3 = 1365 HVN [3]. The hardness of the interface on this sample is lower due to the limited thickness of the oxide layer.

Aluminium Cold Spray Coating on AA7075 Aluminium Alloy Substrate

A photomicrograph of aluminium cold spray coating on AA7075 alloy was obtained (Fig. 4). It shows that the grain of aluminium substrate is elongated with the ratio of 5:1. The flattened grain in the substrate indicates that the aluminium substrate was plastically deformed. The aluminium coating has high percentages of porosity and maximum thickness of ~155µm.

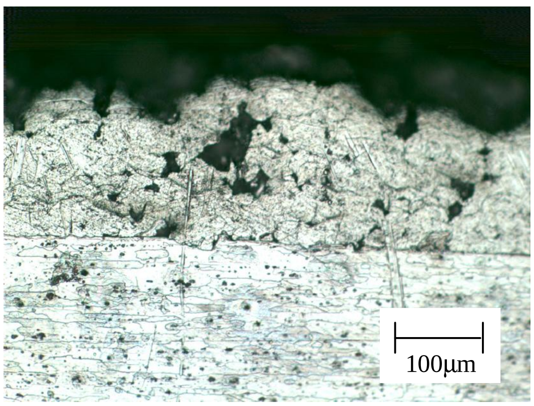

Fig. 4 Photomicrograph showing aluminium cold spray coating on AA7075 aluminium alloy substrate.

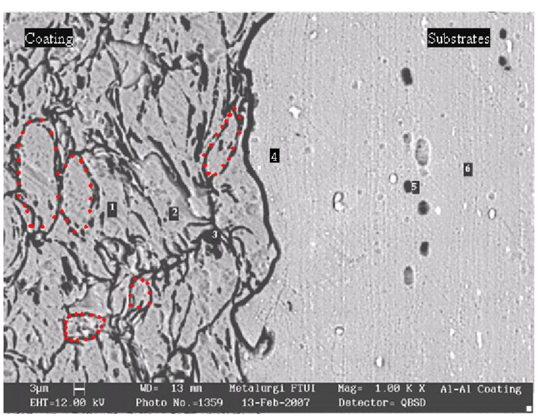

Fig. 5. SEM micrograph (back-scattering mode) of the interface of aluminium cold spray coating on AA7075 aluminium substrate. Areas that were examined are labeled (1), (2), (3), (4), (5) and (6), and the results are presented in Table 2.

Fig. 5 shows that the grain of aluminium substrate is elongated with the ratio of 5:1. Although the EDX point analysis at the interface was unsuccessful, the presence of dark layer with thickness of 2µm may be able to be the evidence of the presence of oxide layer.

Table 2. Microanalysis of cold sprayed aluminium coating on AA7075 aluminium alloy substrate on positions shown in Fig. 5

Position		Chemical Composition, wt. %							
		C	O	Al	Zn	Si	Cr	Cu	Mg
	1	4.79	1.66	rem	-	-	-	-	-
Coating	2	1.9	1.26	rem	-	-	-	-	-
	3	2.48	3.5	rem	4.73	-	-	5.53	-
	4	2.48	4.63	rem	4.99	-	-	5.34	0.52
Substrate	5	2.73	2.28	rem	5.08	-	0.3	4.03	-
	6	2.63	2.34	rem	4.96	-	-	6.06	1.23

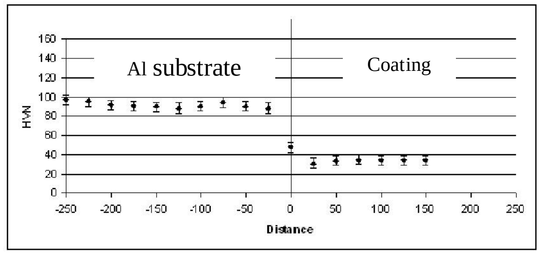

Fig. 6. Vickers microhardness profile of the aluminium cold spray coating on AA7075 alloy, started from the substrate

Based on the microhardness test results (as in Fig. 6), the hardness of aluminium coating is 30 HVN. It is higher than that of the pure aluminium from literature which is 15 HVN. This can be explained by the elongated grains at the coating (see Fig. 4), with grain diameter ratio of 3:1. This may due to deformed particles that may caused of strain hardening upon impact.

Aluminium Cold Spray Coating on 4130 Steel Substrate

The photomicrograph of this sample shown in Fig. 7, in which the aluminium coating has high percentages of porosity and maximum thickness of ~394µm.

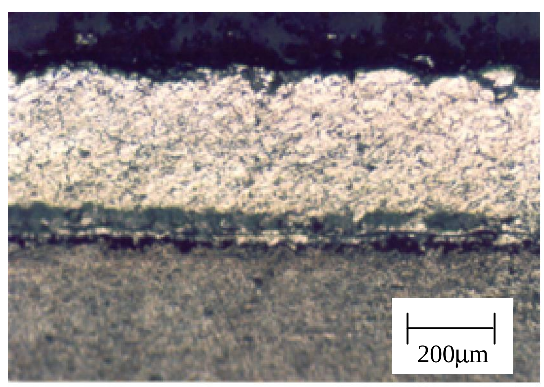

Fig. 7. Photomicrograph showing aluminium cold spray coating on 4130 steel substrate.

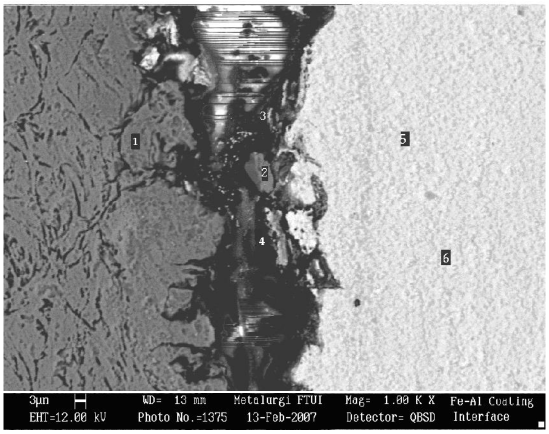

Fig. 8. SEM micrograph (back-scattering mode) of the interface of aluminium cold spray coating on 4130 steel substrate. Areas that were examined are labeled (1), (2), (3), (4), (5) and (6), and the results are presented in Table 3.

Table 3. Microanalysis of cold sprayed aluminium coating on 4130 steel substrate on positions shown in Fig. 8

Position		Komposisi Kimia, wt. %						
		C	O	Al	Zn	Si	Cr	Fe
Coating	1	1.7	0.79	rem	-	0.18	-	-
	2	34.29	7.11	1.69	-	54.66	-	2.25
Interface	3	15.71	42.32	5.03	-	1.32	-	3.51
	4	35.41	28.21	13.9	-	1.68	0.55	15.88
Substrate	5	2.21	2.62	0.67	-	-	1.45	rem
	6	4.43	4.53	0.61	-	-	1.21	rem

Fig. 8 shows delamination between the coating and the substrate. More over, positions 3 and 4 (Table 3) show high amount of oxygen, which may be an evidence of Al_2O_3 formation. However the thickness of oxide layer can not be revealed due to the delamination.

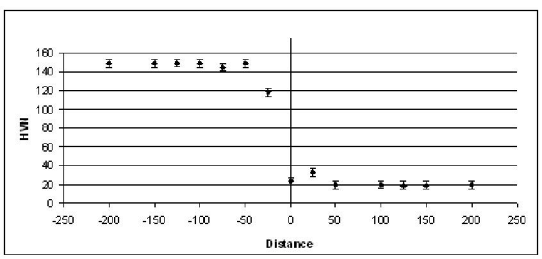

Fig. 9. Vickers microhardness profile of the aluminium cold spray coating on 4130 steel substrate, started from the substrate

Further study was obtained by the microhardness test which results shown in Fig. 8. The hardness of aluminium coating is 20 HVN, which roughly similar with the hardness from the literature. The hardness of the interface is only 20 HVN. This low value may indicates poor quality of adhesion, which also supported by the presence of delamination.

This is in agreement with the literature which explained that the bonding energy is matched up with elastic energy stored in the particle that becomes deformed on impact. If the bonding energy exceeds the energy of elastic deformation a particle can finally bond to the impacted surface. Otherwise, the particle will be reflected off the surface. In this case, the aluminium particles have higher deformability than the steel substrate. Hence, aluminium particle's energy of elastic deformation defeated the bonding energy, resulted in a poor quality of adhesion at the interface[4, 5].

Hardness of 4130 steel is 163 HVN[6] which is roughly the same with the sample used in this project.

Comparison of Aluminium Cold Spray Coating in ZE41A-T5 Magnesium, AA7075 Aluminium Alloys and 4130 Steel Substrates

Table 4 shows comparison of various characteristics of aluminium cold spray coating on three different substrates. The hardness of aluminium cold spray coating on ZE41A-T5 magnesium substrate is 50 HVN, while that on AA7075 and 4130 steel substrates are 30 HVN and 20 HVN, respectively. The highest hardness of coating is revealed on magnesium substrate. This seems to be due to low porosity and highly deformed particles that may induce strain hardening within the coating. The high deformation indicates by the high grain diameter ration (ℓ_1:ℓ_2) of 5:2, in comparison to that of aluminium and steel substrates.

Table 4. Comparison of coating characteristics on ZE41A-T5 magnesium, AA7075 aluminium alloys and 4130 steel substrates

Characteristic	Substrate		
	ZE41A	AA7075	4130 steel
Coating			
- ratio ℓ_1:ℓ_2	5:2	3:1	2:1
- min ℓ_1 (μm)	5	9	8
- max ℓ_1 (μm)	30	30	20
- max thickness (μm)	~ 292	~ 155	~ 394
- porosity	low	medium	medium
- hardness (HVN)	50	30	20
Interface			
- oxide (wt.%)	32.1	-	42.32
- oxide layer thickness	1 μm	2 μm	N/A
- hardness (HVN)	60	50	20
- porosity	low	medium	N/A due to gap
Substrate			
- hardness (HVN)	50 – 70	85 – 100	110 – 150

The coating on aluminium substrate has higher hardness than that on steel substrate; that maybe due to higher grain diameter ratio.

Aluminium oxide layer formed at the interfaces, that can be proven with the high amount of oxygen. There are 1 μm and 2 μm oxide layers for the sample with magnesium and aluminium substrates, while oxide layer at steel substrate sample can not be revealed due to the gap. Magnesium sample posses the highest hardness of interface due to low percentages of porosity, while the steel sample has the lowest hardness at interface due to the presence of delamination.

Both coating and the interface of aluminium substrate show high percentage of porosity, which indicates poor quality of adhesion. This may due to the tenacious oxide layer that covers both the particle and the surface of substrate, which suppresses the surface activity.

At all the samples, the interface is not a straight line that may due to generation of interface curvature resulted from shear instability[7,8]. The kinetic energy generated due to the plastic flow at the interface produces differential interfacial velocities. Differential interfacial velocities disturb the flow and generate shear instability giving curvature along the interface. It may obviously be expected that this phenomenon will dominate at the interfacial layer towards mechanically interlocking the adjacent surfaces.

Conclusion

The study concluded that:

1. The aluminium coatings on all the substrates show elongated grains morphology, due to strain hardening upon impact. This supported with the hardness of 20 – 50 HVN, which is higher than the literature. The aluminium coating has thickness of 155 – 394 µm and porosities with variety of percentages.
2. Layers of Al_2O_3formed with the thickness of 1 – 2 µm at the interface of all samples, which due to the reaction of aluminium particles with oxygen. The hardness of interface ranges from 20 – 60 HVN and it depends on the percentages of porosity.
3. The aluminium cold spray coating on the ZE41A-T5 magnesium substrate has the highest hardness and the lowest porosity percentages, which may indicate a good quality of bonding.
4. The possible mechanism of bonding is mechanical interlocking. This is supported by the evidence that the interface at the entire samples is not a straight line that may due to generation of interface curvature

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