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Optimum Surface Roughness of Aluminum Coating to Protect Equipment from Corrosion with Arc Thermal Spray Aluminum Methods

Welly Setyawan[1*], Johny Wahyuadi M[2]
1. PT Pertamina (Persero)
2. Metallurgy and Materials Engineering - Faculty of Engineering, University of Indonesia
* Email: welly.setyawan@pertamina.com

Abstract. Oil and gas production equipment, especially offshore which is often exposed to seawater vapor is susceptible to corrosion on the surface. Aluminum coating can be used to solve this problem. In this study, an Aluminum coating of 200 - 250 µm thickness is produced using *arc thermal spray* technology, with 95.05% aluminum wire as feedstock and a standoff distance of spraying ~300 mm to make the material corrosion-resistant. The substrate surface coarsening is done by grit blasting technique using abrasive aluminum oxide at 140-280 mm spray distance and 3-6 bar pressure. Observations were carried out in four samples with different surface roughness variations: Surface roughness of substrate about 30-50 µm, Surface roughness of substrate about 60-80 µm, Surface roughness of substrate more than 120 µm, and Surface roughness of the substrate material *as it is* with no blasting, about 3-27 µm. The adhesion strength of aluminum coating on the non-blasting substrate has the smallest value and fails in a series of tests. Surface roughness of 60-80 µm produces the best adhesion. The adhesion strength is influenced by the mechanical *interlocking* bond between the coating and the substrate. The rougher surface has a stronger interlocking bond that increases adhesiveness. However, the excessively high surface roughness reduces the bond strength. The adhesion strength of the aluminum coating increases with increasing surface roughness of the substrate to a certain degree of roughness that does not exceed 80 µm. The better the adhesion of the coating, the more protected the material will be from corrosion.

Keyword(s): *surface preparation; thermal spray aluminum; coating; corrosion prevention*

1 Introduction

Aluminum coatings by the *arc thermal spray* method can be used effectively as corrosion protection in the marine environment [1]. The parameters affecting the quality of aluminum coating with Thermal Spray Aluminum (TSA) technology consist of three factors, i.e. substrate surface condition; coating properties; and spraying procedure [2]. Surface conditions such as cleanliness and roughness will affect the quality of the adhesion bond between the coating and the substrate [1]. Poor adhesion bonds between coating and substrate (protected materials) cause premature failure, which is quite prevalent in the field. To overcome these problems, it is necessary to do surface conditioning (*surface preparation*) of the material to be coated. Surface preparation on TSA applications especially for carbon steel materials uses the grit blasting method to obtain the degree of cleanliness and roughness. So, it is necessary to find out the efficient surface roughness value for TSA applications on carbon steel materials.

The purpose of this study is to understand the effect of surface conditioning, especially the substrate surface roughness parameters on the adhesion strength of the aluminum layer of arc-TSA coating on carbon steel material, to determine the proper surface roughness parameter, and to find out the value of bonding between substrate and aluminum coating.

2 Background

Thermal spray coating is a surface engineering technique by depositing particulates in liquid, semi-liquid or solid form by heating the feedstock material and being driven as individual particles or droplets onto a surface (substrate) to form a thin layer with a lamellar structure [3]. Several studies have been conducted to determine the characteristics of the coating produced by thermal spray technology. Abd Malek and Nor H. Saad, et al. 2013 [2], in their paper discuss the use of aluminum thermal spray instead of organic coatings to improve the protection of corrosion material in the oil and gas industry. Surface preparation was performed using abrasive blasting at 4-6 bars to meet the surface roughness of the blasted surface in the range of 75 – 110 μm. All samples had passed the minimum requirement with an average of 10 MPa for Pull off Test and no crack appeared in Bend Test for aluminum coating with thickness in a range from 200 to 400 μm. V.R.S. Sá Brito, I.N. Bastos, H.R.M. Costa, 2012 [4], evaluated the mechanical and metallurgical properties of five metallic coatings produced by thermal spray on carbon steel. His study gets that the adhesion bond strength of thermal spray metallic coating varied from 14.0 MPa to 25.3 MPa.

Henry Begg, Melissa Riley, and Heidi de Villiers Lovelock, 2015 [5] in his paper investigate the mechanization of the grit blasting process for thermal spray coating applications, especially the effect of blast parameters which is a part of surface preparation that affect the adhesion bond strength between a thermal spray coating and substrate. The investigation resulted in that surface roughness was found to be most affected by blast pressure, media size, and traverse speed.

Varacalle, et.al, 2006 [6], in his paper that discusses the effect of grit-blasting on substrate roughness and coating adhesion showing that surface roughness 51.6 to 88.6 μm is the optimum value for Zn-Al coating application on mild steel material for thermal spray process. Surface roughness, R_t about 51.6 to 88.6 μm produces coating adhesion bond strength ranging from 8 – 9 MPa. Surface roughness, R_t more than 88 μm, such as 92 - 138 μm, produces smaller adhesion strength, 7.8 – 8.5 MPa.

Paredes, Amico, and d'Oliveira in 2005 [7] carry out experiments with an electric arc spray process to deposit aluminum coating to the mild steel substrate. The surface roughness of substrate (R_y) 50 – 60 μm produces adhesion strength of coating around 17.9 Mpa, R_y 60 – 70 μm produces adhesion of 15.8 MPa, and R_y 70 – 80 μm produces adhesion of 13.7 MPa.

3 Methods

Specified surface roughness is obtained through the grit blasting process. Roughness values are based on depth profile measurements at some point using ASTM D 4417 standards. Consists of four substrate samples of roughness variations: surface roughness of substrate 30-50 μm, surface roughness of substrate 60-80 μm, the surface roughness of substrate >120 μm, and without grit blasting sample. Abrasive grit blasting using aluminum oxide grade C size 24 and 16 mesh. Blast pressure set to 4 bar - 6 bar with standoff distance 150 mm and 70 ~ 80^{o} blast angle.

Aluminum spraying is done with a standoff distance of 300 mm in the atmospheric environment. The thickness of the aluminum coating is measured with a target thickness in the range of 200 - 250 µm. Aluminum spraying method using wire-arc thermal spray manual technology with aluminum wire composition of 95,05% Al; 4.7% Si and 2 mm in diameter as feedstock material.

The various test of samples carried out after 7 days since the TSA spraying process has been completed. Bending testing method using ASTM D522 standard, pull-off test method using ASTM D4541 standard, salt spray test using ASTM B117 method, and microhardness using ASTM E384 Vickers standard.

Metallography observation was carried out using an optical microscope and also observation using SEM. Salt spray test was performed using 5% NaCl salt solution for 72 hours, where the sample was scratched in crosses at the coating area. Observations were made by visual observation based on the ASTM D 1654-79 standard, where the scratched area was further refined to evaluate whether there was a coating layer that had peeled off. Tests of coating bonding strength by pull-off method were performed using *Pull-Off Adhesion Tester* as shown in Figure 1.

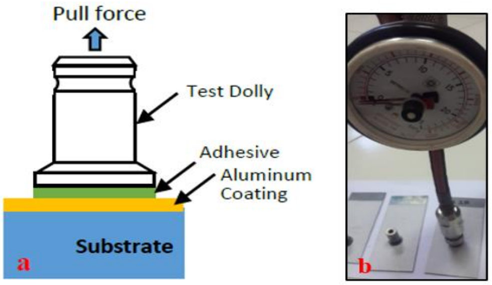


Figure 1. Pull-off test method (a) test schematic, (b) adhesion tester tools

4 Result and Discussion

The results of the surface roughness profile measurements for the four sample variations before the coating is applied are summarized in Table 1.

Table 1. Surface Roughness Profile of Grid Blasting

Point	Sampel-1	Sampel-2	Sampel-3	Sampel-4
1	36 µm	70 µm	124 µm	18 µm
2	38 µm	80 µm	147 µm	27 µm
3	35 µm	69 µm	144 µm	21 µm
4	30 µm	63 µm	134 µm	8 µm
5	40 µm	71 µm	140 µm	10 µm
6	34 µm	74 µm	131 µm	3 µm
7	42 µm	64 µm	126 µm	7 µm
8	37 µm	63 µm	128 µm	20 µm
9	31 µm	66 µm	130 µm	5 µm
10	44 µm	64 µm	132 µm	12 µm
mean	36,7±7,3 µm	68,4±11,6 µm	133,6±13 µm	13,1±13 µm

The visual observation of the aluminum coat is seen in Figure 2. All samples have actual measurements of coating thickness values ranging from 226 µm to 251 µm. The surface roughness of aluminum coating for all samples has almost the same value. This indicates that the entire surface of the substrate for all samples is covered by an aluminum layer so that the surface roughness of the aluminum coating is not affected by the roughness of the substrate.

Figure 2. Samples After Aluminum Coating Applied

The microstructural observation of the cross-section is shown in Figure 3. From the microstructure observation, it is seen that the aluminum layer formed in the form of a horizontal lamellar structure parallel to the surface of the substrate. The heterogeneity of the microstructure of aluminum layer is evident, especially the oxide and porosity. Porosity occurs among the substrate and aluminum droplets, and between the droplets themselves. The porosity between the substrate and the coating layer results in decreased adhesion strength, while the porosity in the aluminum itself makes the cohesion bond decrease. Porosity may be formed by the impulse of the pressurized gas during the spraying process and also the presence of non-melt (semi-molten) droplet particles as well as splat sparks [8]. However, the porosity that occurs in the coating does not penetrate deep enough to reach the interface substrate – coating so that the barrier function against the corrosive environment is still working.

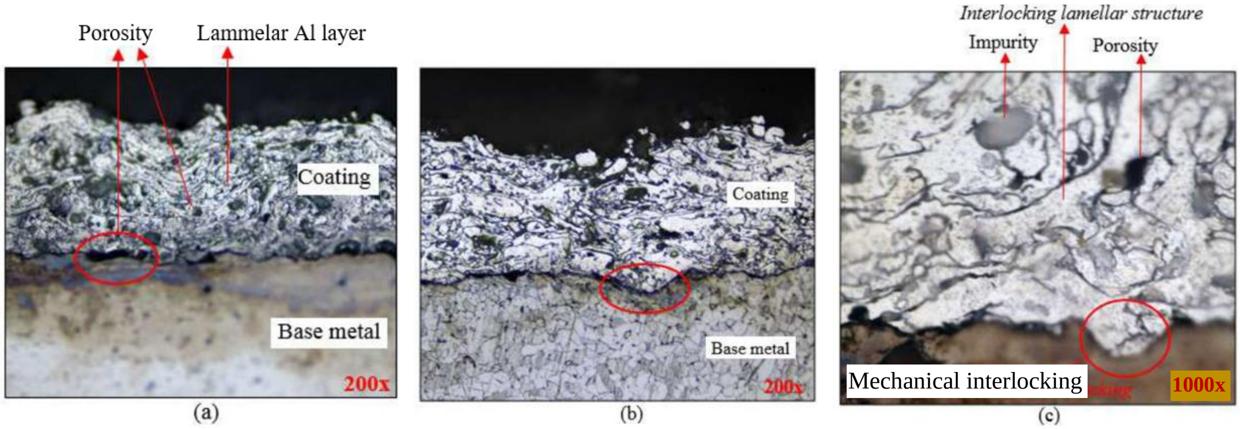
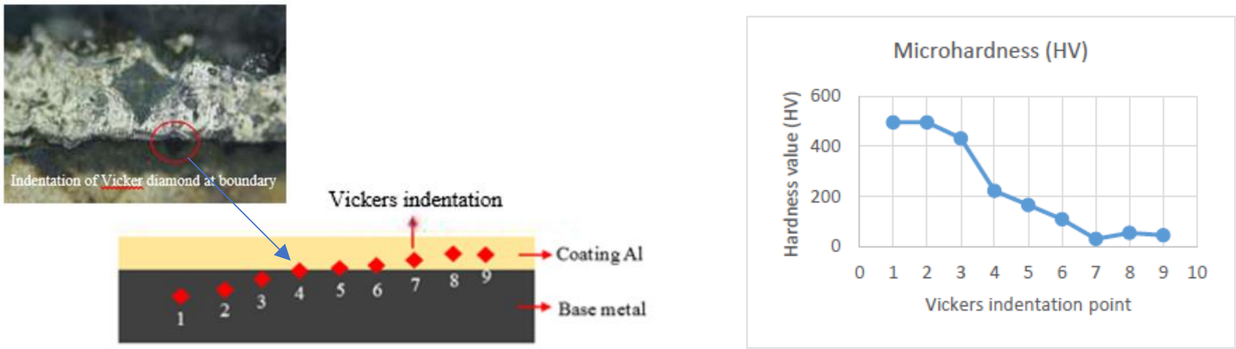


Figure 3. TSA coating cross-section microstructure: (a) sample with surface roughness 30-50 µm; (b) sample with surface roughness >120 µm; (c) sample with surface roughness 60-80 µm

Porosity and impurities that form between coating and substrate will decrease adhesion strength of the coating. The spraying of melted aluminum particles (splat) onto the substrate surface without pre-heating causes heat from the splat to be rapidly absorbed by the cold substrate resulting in no homogeneous *wetting effect* and promoting particle disintegration that results in decreased adhesion bond [7]. Excessive amounts of oxide can decrease the strength of the cohesive bond and the adhesion of aluminum coating [9]. The aluminum material that infiltrated into the valley slit of the substrate forms a mechanical bond that strengthens the adhesion of the coating [10]. The mechanical bond or called an *interlocking* bond dominates so that the coating's adhesiveness is affected by the substrate roughness [10,11]. W.J. Trompetter, 2005 in his research journal, proved that the bond between the coating and the substrate on the thermal spray coating is dominated by mechanical interlocking and no chemical bonding [10]. The inter-droplet bonds of aluminum are formed by strongly lamellar interlocking structures [11], as shown in Fig. 3(c).

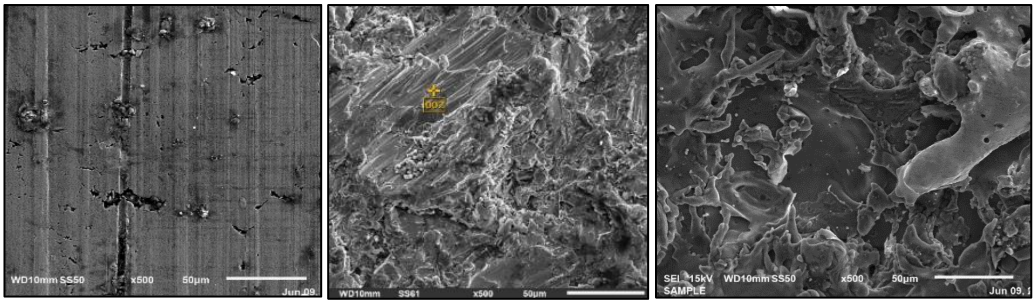
Microhardness testing is performed to see whether there is any diffusion between the coating and the substrate. Microhardness testing is done with an inter-point indented distance of 100 μm, as illustrated in Figure 4(a), while the test result is summarized through the graph in Figure 4(b).



(a) **(b)**

Figure 4. Microhardness test: (a) Illustration of indentation traces of micro-Vickers;
(b) Microhardness measurement graph

Indentation points 5 and 6 are on the base metal-coating border. The measurement of hardness on the border produces values that do not represent base-metal value or aluminum value since the indenter of Vickers presses both base-metal and aluminum areas simultaneously. Based on the trend of hardness values shown in the graph in Figure 4(b), there is no evidence of diffusion interfaces between materials, so the diffusion process does not occur.



(a) **(b)** **(c)**

Figure 5. Surface morphology: (a) substrate before blasting, (b) after blasting (c) aluminum coating

Figure 5(a) shows the observation image using SEM with 500x magnification on the base metal (substrate) surface before grit blasting. Visible smooth surfaces result in weak adhesion-mechanical bonding when aluminum coating is applied. Figure 5(b) shows the morphology of the surface roughness of the substrate after blasting. The roughness increases the adhesion strength of the aluminum coating. Figure 5(c) shows the surface morphology of the aluminum coating. Visible uneven surfaces, such as spark traces, are composed of droplets and there are small porosities on the surface. The results of the pull-off test show that the sample with a surface roughness of 68.4 ± 11.6 μm has the strongest adhesion bond. The parameter of surface roughness affects the adhesion strength, this is because the dominant bonding mechanism is the interlocking mechanical bond, that shown by microstructure observation, microhardness testing, and in line with some earlier studies [7,10,11,12]. A comparison of adhesion strength values for all samples can be seen in Table 2.

Table 2 Pull-of Test Result of Aluminum Coating

Sample	Surface Roughness	Adhesion strength of Coating
1	36,7±7,3 μm	6,0 MPa
2	68,4±11,6 μm	8,0 MPa
3	133,6±13,4 μm	6,1 MPa
4	13,1±13 μm	4,1 MPa

The excessively high surface roughness value reduces adhesion bonding between coating and substrate, as occurs in samples with a surface roughness of more than 120 μm. Thus, the adhesion strength of the aluminum layer increases with an increased surface roughness of the substrate to a certain degree of roughness, i.e., not exceeding 120 μm. The relationship between surface roughness to adhesion is illustrated by the graph in Figure 6.

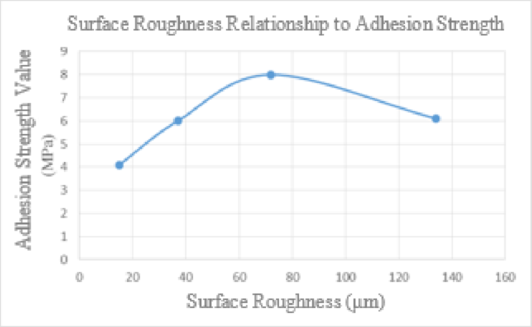


Figure 6. Graph of surface roughness relationship to adhesion strength

The non-blasting sample does not pass the bending tests due to the peeling of the aluminum coating. The failure is caused by the poor adhesion bonds between aluminum coating and substrate.

Observation after salt spray test on scratch area resulted did not occur widening or peel coating on samples which in grit blasting. The failure of the salt spray test is experienced by the sample without grit blasting, where the aluminum layer is peeled and corrosion occurs on the substrate surface below it.

5 Conclusions

The protection of material from corrosion can be done by applying aluminum coating on the surface. The quality of aluminum coating formed by arc thermal spray technology on carbon steel is influenced by adhesion strength between coating and substrate, while adhesion strength is affected by surface roughness and cleanliness of substrate. The control of surface preparation becomes very important in the application of thermal spray aluminum (TSA). The performance of aluminum coating that applied on substrate with no surface preparation is failed in various tests.

Mechanical bonding (mechanical interlocking) is the dominant bonding that affects adhesion strength in the TSA coating, and there is no evidence of diffusion mechanisms was occur. The greater value of substrate roughness produces a higher adhesion strength to a certain degree of roughness. The optimal surface roughness range for TSA applications in carbon steel substrate is 60 μm to 80 μm.

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