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Analysis of Adhesion Strength and Surface Hardness of 6061 Aluminum Alloy Resulting from Powder Coating with Variations in Sandblasting Process Time

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Abstract--*The success of powder coating is highly dependent on specimen preparation, one of which is sandblasting. This study aims to analyze the effect of variations in sandblasting time on surface roughness, adhesion strength, and surface hardness of powder coated 6061 aluminum alloy. The research method used was quantitative experimental. Specimens measuring 50 mm × 50 mm × 3 mm were sandblasted with time variations of 15 seconds, 35 seconds, and 55 seconds, and their surface roughness was measured. Furthermore, the specimens that have undergone the sandblasting process will be continued for the powder coating process and tested for adhesion strength and surface hardness. The results showed that the highest roughness, adhesion strength, and surface hardness were found in the 55-second variation with a roughness value of 6.18 µm, an adhesion strength value of 5.63 MPa, and a surface hardness value of 14.45 VHN. This shows that the longer the sandblasting time, the higher the surface roughness, the higher the adhesion strength and the surface hardness.*

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1. INTRODUCTION

Component production in the automotive industry commonly utilizes aluminum and its alloys, such as valves, rims, pistons, engine caps, cylinder heads, and cylinder blocks [1]. For automotive components like rims, it is not uncommon for vehicle owners to seek re-coating to enhance the aesthetics of their personal vehicles. However, re-coating is not a straightforward process, as improper procedures can result in paint peeling and suboptimal adhesion. Therefore, a method that yields a stronger and more durable coating is needed. One such coating method employed is powder coating [2].

Powder coating involves the application of a powdered paint that carries a static charge when sprayed onto a metal material, followed by heating in an oven to cure and adhere the paint to the material surface [3], [4], [5]. The success of powder coating is significantly influenced by the surface preparation process, which directly affects the adhesion strength of the coating to the metal material [6]. Sandblasting is recognized as one of the most effective metal surface cleaning methods due to its ability to remove contaminants, low cost, minimal pollution, rapid execution, enhancement of surface roughness and adhesion properties, and absence of workpiece size limitations [7], [8], [9], [10], making this cleaning method widely preferred. The phrase "no size requirements" highlights the flexibility of the sandblasting process to accommodate complex and contoured workpiece geometries [11]. The sandblasting process utilizes abrasive materials like aluminum oxide, silica sand, glass, or iron grit to dislodge contaminants [10]. Specimens subjected to sandblasting exhibit cleaner and rougher surfaces, thereby improving the adhesive properties for various coating applications [12].

Several studies on sandblasting have been conducted. Research by Peñuela-Cruz et al. [13] on the effect of pressure, distance, and their combinations revealed that roughness values increased significantly with increases in all three variations, and hardness values increased only with increases in pressure variation regardless of distance variations. Bechikh et al. [7] investigated the influence of pressure, angle, and sand granulometry variations, demonstrating that as sandblasting pressure and sand granulometry increased, the average surface roughness of specimens also increased, while specimens treated with the lowest glace sand granulometry exhibited the highest surface free energy. Conversely, variations in sandblasting angle primarily affected chemical composition and wettability rather than roughness. Khoir et al. [14] considered the use of varying aluminum oxide grit sizes (60, 80, and 100) as abrasive materials in sandblasting processes on corrosion rate and adhesion strength. The test results indicated that smaller aluminum oxide grit sizes resulted in higher paint adhesion strength and lower corrosion rates. Pamungkas et al. [15] studied the effect of sandblasting nozzle distance on coating thickness and corrosion rate. The research showed a correlation between sandblasting nozzle distance and surface characteristics and material corrosion resistance. Specifically, a decrease in nozzle distance positively correlated with an increase in surface roughness and coating thickness, and negatively correlated with corrosion rate.

Based on this background, it is evident that the adhesion strength and surface hardness of the resulting coating are influenced by pre-treatment processes such as sandblasting. Air pressure, distance, angle, and nozzle diameter can affect the surface roughness of the material during sandblasting [8]. However, there is relatively limited research available on the effect of sandblasting process duration on surface roughness to enhance coating adhesion strength and surface hardness.

Therefore, this study aims to evaluate the effect of surface roughness of aluminum alloy 6061 resulting from variations in sandblasting process time on the adhesion strength and surface hardness of the powder coating.

2. METHODOLOGY

The research methodology employed will be experimental with a quantitative approach to determine the surface roughness values resulting from the sandblasting process. The material used is aluminum alloy 6061 with dimensions of 50 mm × 50 mm × 3 mm. The sandblasting process will be conducted with variations in spray time of 15 seconds, 35 seconds, and 55 seconds, and the results will be visually inspected. Subsequently, each specimen will be coated, followed by adhesion strength and surface hardness tests. The dimensions of the test specimens are presented in the Figure 1.

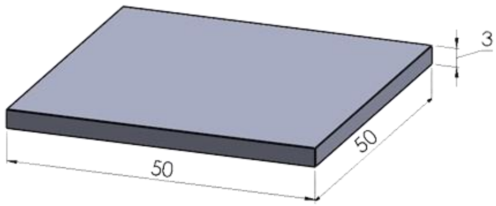


Figure 1. Dimensions of test speciment

2.1 Research Workflow

This research followed a sequence of procedures and workflows, including literature review, specimen preparation, sandblasting process, surface roughness testing, powder coating process, adhesion strength and hardness testing, and results analysis for decision-making. The research workflow is presented in a flowchart as depicted in Figure 2.

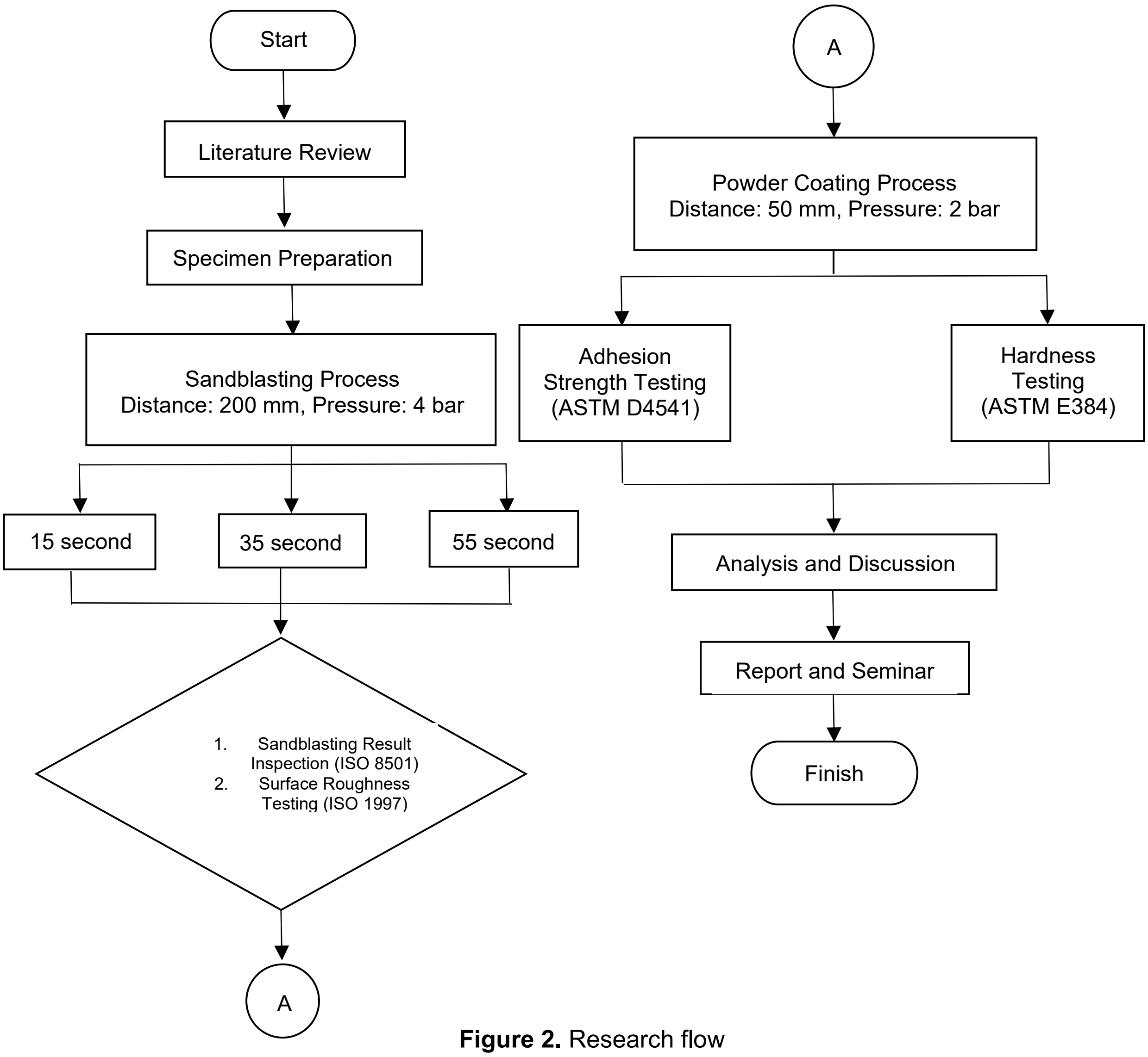


Figure 2. Research flow

2.2 Sandblasting

The working principle of sandblasting is based on utilizing a high-pressure air stream to accelerate abrasive particles and project them onto the surface of a workpiece [12]. In this study, the sandblasting process was conducted using glass beads as the abrasive material with a spraying pressure of 4 bar, an angle of 90º, and a distance of 200 mm. The spraying duration was varied at 15 seconds, 35 seconds, and 55 seconds.

2.3 Powder Coating

The working principle of powder coating involves utilizing low-pressure air and generating static electricity when paint particles are sprayed onto a metal material, which is subsequently heated in an oven to solidify the paint and ensure proper adhesion to the material surface [3], [4], [5].

In this study, powder coating was performed using Jotun Super Durable paint with a single layer application at a coating speed of 0.01 m/s with a spraying pressure of 2 bar, an angle of 90º, and a distance of 50 mm. The specimens were heated at a temperature of 200ºC for a duration of 15 minutes after the powder coating process.

2.4 Surface Preparation

A. Visual Testing

This visual inspection procedure adheres to the ISO 8501-1 standard [16], an international standard that provides visual references in the form of images to assess the cleanliness level of surfaces prior to the application of paint or related coatings. This standard stipulates that the surface must be free from contaminants visible to the naked eye, without requiring magnification. In the context of sandblasting, the established standard cleanliness level is Sa 2.5. Specifically, Sa 2.5, as defined within ISO 8501-1, indicates a ‘very thorough blast cleaning’ where nearly all rust, mill scale, and other contaminants have been removed from the surface. The remaining traces of contaminants are visible only as slight shadows or streaks, representing a high degree of surface cleanliness essential for ensuring optimal adhesion and longevity of subsequent coatings.

B. Roughness Testing

To determine the surface roughness level after the sandblasting process, testing was conducted using a Mitutoyo Surftest SJ-210 surface roughness tester, adhering to the ISO 1997 standard [17]. The operational principle of this instrument is based on the use of a stylus that moves linearly along the surface of the tested specimens. The vibrations generated by the interaction between the stylus and the specimen surface are detected by a sensor, which subsequently converts these mechanical vibrations into an analog electrical signal. This signal is then transformed into a digital signal by the data processing unit within the instrument. The digital signal is processed using specific algorithms to calculate and display the surface roughness value in micrometers.

2.5 Pull-off Adhesive Testing

Adhesion strength testing was conducted using the pull-off adhesive method with an adhesion tester, in accordance with the ASTM D4541 standard [18]. The procedure involved attaching a 20 mm diameter dolly to the coating surface using a 1:1 mixture of epoxy adhesive and hardener, and allowing it to cure for 24 hours until fully hardened. After curing, the outer surface around the dolly, where the adhesive had made contact, was cleaned using a dolly cutter. Subsequently, adhesion strength testing was performed by attaching the top of the dolly to the adhesion tester. This test was carried out to determine the adhesion strength of the powder coating layer to the sandblasted specimens.

2.6 Hardness Testing

Hardness testing was performed using a microvickers hardness tester, in accordance with the ASTM E384 standard [19]. The fundamental principle of this test involves the use of a diamond pyramid indenter with an opposing face angle of 136º. When this indenter is applied to the test object surface under a controlled load, a permanent indentation or impression is formed, which can be visually observed through an optical microscope.

In this research, the hardness test was conducted by taking five test points on the specimen surface to determine the surface hardness value of the powder coating. The surface hardness value calculation can be performed using the following equation:

$$VHN = \frac{2P\ \sin\left(\frac{\theta}{2}\right)}{d^2} = \frac{1.854 \times P}{d^2} \quad (1)$$

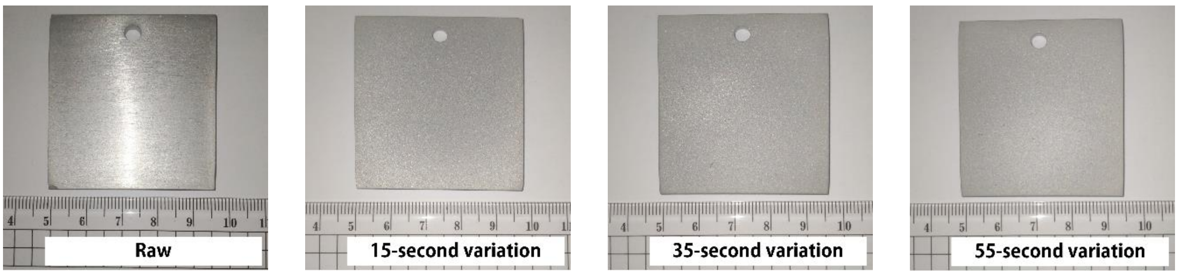
Where:

P : Indentation load (kgf)
d : Average diagonal length (mm)
θ : Angle between indenter faces (º)

3. RESULT AND DISCUSSION

3.1 Visual Testing Results

Visual testing was carried out to determine the level of cleanliness obtained after carrying out the sandblasting process. The test was carried out visually based on the ISO 8501 standard [16]. The cleanliness results of 6061 aluminum alloy in the sandblasting process are presented in Figure 3.



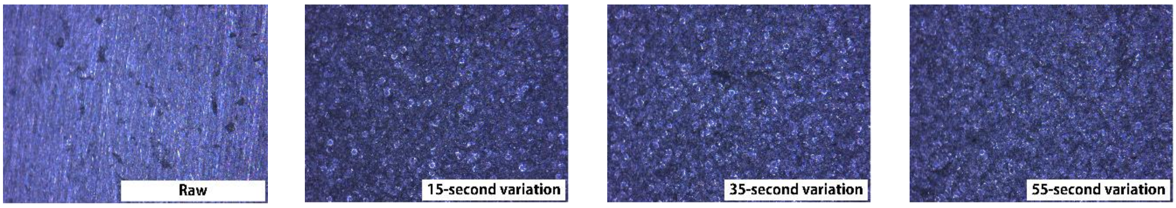


Figure 3. Visual test results

Based on visual assessment, the surface cleanliness level of the material corresponds to the blast cleaning category designated as Sa 3. At this level, examination without magnification reveals a surface devoid of visible oil, grease, and particulate contamination. Furthermore, the surface is free from mill scale, rust, paint coatings, and any foreign matter, exhibiting a uniform metallic appearance. The specimen surface demonstrates homogeneity in its visual characteristics and lacks any discernible staining. The success in achieving the Sa 3 cleanliness level shows that the sandblasting process has been carried out optimally.

3.2 Surface Roughness Testing Results

Roughness testing was carried out to determine the surface roughness value of 6061 aluminum alloy for the sandblasting process. This test uses a surface roughness tester based on the ISO 1997 standard [17]. The test points were taken at three points diagonally to the sample. The test results for surface roughness of 6061 aluminum alloy after the sandblasting process are presented in Table 1.

Table 1. Roughness test results

Variation (seconds)	Specimen No.	Test Point (µm)			Average (µm)
		A	B	C	
15	1	3.654	3.561	3.677	3.631
	2	3.038	3.187	3.074	3.100
	3	2.727	2.927	2.748	2.801
Average Roughness Value at 15 Second Variation					3.177
35	1	4.097	3.935	3.902	3.978
	2	3.677	3.570	3.537	3.595
	3	4.655	4.780	4.747	4.727
Average Roughness Value at 35 Second Variation					4.100
55	1	6.499	6.457	6.438	6.465
	2	6.975	6.863	6.796	6.878
	3	5.353	5.127	5.111	5.197
Average Roughness Value at 55 Second Variation					6.180

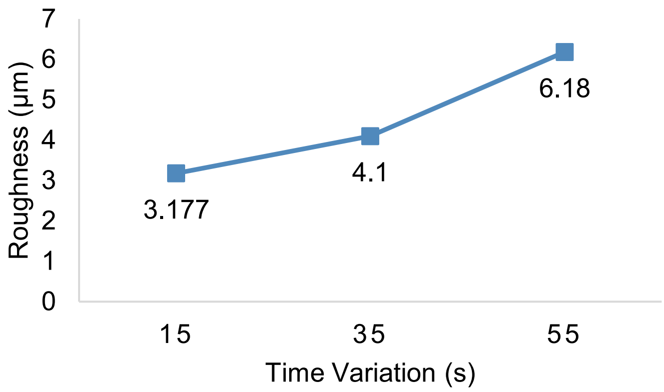


Figure 4. Graph of roughness value vs. sandblasting time variation

Based on the experimental data presented, there is a positive correlation between sandblasting duration and surface roughness value. This pattern indicates that the longer the specimen is exposed to abrasive material, the higher the resulting roughness level. The highest average roughness value was found in the 55 second time variation with a roughness value of 6.18 µm, followed by the 35 second variation with a roughness value of 4.1 μm, and the lowest in the 15 second variation with a roughness value of 3.177 μm. The results of this test are supported by research conducted by Pradana and Kromodiharjo [16], stating that surface roughness increases with increasing sandblasting process time.

3.3 Adhesion Strength Testing Results

Adhesion strength testing of the coating was carried out to determine the bond strength value of the coating on the surface of 6061 aluminum alloy for variations in sandblasting time. This test uses an adhesion tester based on the ASTM D4541 standard [16] by attaching a 20 mm diameter dolly to the specimen surface using epoxy glue and a 1:1 ratio hardener for 24 hours. This process aims to allow the glue to freeze and the dolly to adhere perfectly to the coating layer. The pull-off adhesive test results, which include quantitative and qualitative data regarding the type of failure, are summarized in Table 2.

Table 2. Adhesion strength test results

Variation (seconds)	Specimen No.	Adhesive Failure (%)	Cohesive Failure (%)	Glue Failure (%)	Adhesion Strength (MPa)	Average (MPa)
15	1	75	10	15	2.66	2.65
	2	70	20	10	2.84	
	3	55	0	45	2.46	
35	1	0	0	100	4.66	4.22
	2	40	0	60	3.82	
	3	45	0	55	4.18	
55	1	5	0	95	6.68	5.63
	2	60	0	40	4.03	
	3	10	0	90	6.19	

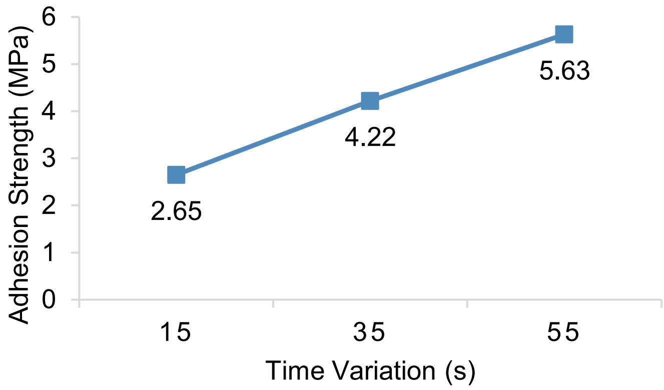


Figure 5. Graph of adhesion strength value vs. sandblasting time variation

Based on the data presented, it can be seen that the adhesion strength increases with increasing sandblasting process time. The highest average adhesion strength was found in the 55 second time variation with a value of 5.63 MPa, followed by the 35 second time variation with a value of 4.22 MPa, and the lowest in the 15 second time variation with a value of 2.65 MPa. The results of this test are supported by research conducted by Khoir et al. [14], stating that rougher surfaces produce stronger adhesion between the coating layer and the substrate.

3.3 Surface Hardness Testing Results

The hardness value of the powder coating layer on the surface of 6061 aluminum alloy was tested using a microvickers hardness tester based on the ASTM E384 standard [19]. In this testing procedure, a diamond pyramid indenter with an inter-surface angle of 136° was employed to create indentations on the powder-coated layer surface. The applied indentation load was 0.05 kgf.

Determination of the VHN of the specimen surface at each test location follows the calculation using equation (1). An example of the calculation is presented as below.

Given : P = 0.05 kgf
d_1 = 87.12 μm = 0.08712 mm
d_2 = 87.74 μm = 0.08774 mm
d = 87.43 μm = 0.08743 mm

Then, it can be substituted into the following solution formula:

$$VHN = \frac{1.854 \times P}{d^2}$$

$$VHN = \frac{1.854 \times 0.05}{(0.08743)^2}$$

$$VHN = 12.12 \; {kgf}/{mm^2}$$

The following are the hardness test results of the powder coating layer, presented in Table 3.

Table 3. Surface hardness test results

Variation (seconds)	Specimen No.	Test Point (VHN)					Average (VHN)
		A	B	C	D	E	
15	1	12.12	12.43	11.77	12.12	12.38	12.17
	2	12.65	12.71	13.40	12.38	12.85	12.80
	3	12.75	13.02	12.76	13.07	13.61	13.04
Average Hardness Value at 15 Second Variation							12.67
35	1	13.69	13.89	12.64	14.25	13.13	13.52
	2	11.13	14.02	13.33	12.22	13.95	12.93
	3	14.96	14.26	14.15	14.75	14.12	14.45
Average Hardness Value at 35 Second Variation							13.63
55	1	13.79	13.78	14.44	16.22	13.88	14.42
	2	13.46	13.75	14.24	13.80	15.14	14.08
	3	14.67	14.71	14.65	14.90	15.26	14.84
Average Hardness Value at 55 Second Variation							14.45

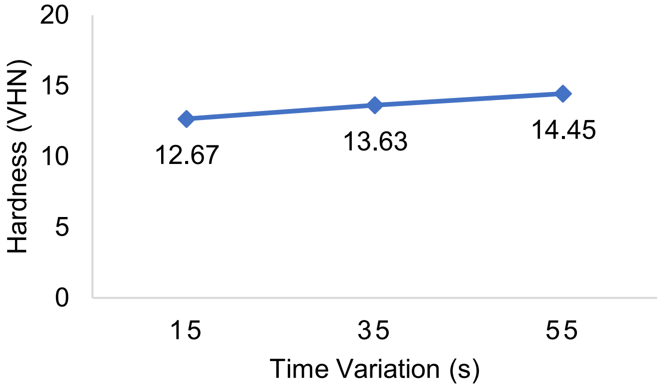


Figure 6. Graph of hardness value vs. sandblasting time variation

The sandblasting process increases surface roughness, which in turn can absorb more particles from the powder paint so that the powder coating layer becomes denser and resistant to scratches [15], so this has implications for increasing surface hardness. From the hardness test results after the powder coating process, it was found that there was a tendency for an increase in the hardness value of the coating layer with increasing sandblasting process time. The highest average hardness value was found in the 55 second time variation with a value of 14.45 VHN, followed by the 35 second variation with a value of 13.63 VHN, and the lowest in the 15 second variation with a value of 12.67 VHN.

4. CONCLUSION

Based on the test results, a positive correlation was found between surface roughness, adhesion strength, and surface hardness after the sandblasting and powder coating processes on 6061 aluminum alloy. The results showed that the highest roughness, adhesion strength, and surface hardness were found in the 55-second variation with a roughness value of 6.18 µm, an adhesion strength value of 5.63 MPa, and a surface hardness value of 14.45 VHN. This means that the higher the surface roughness value produced by the sandblasting process, the higher the adhesion strength and surface hardness values achieved after the powder coating process. This is because the rough surface creates mechanical interlocking between the powder coating layer and the substrate.

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