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Influence of Pre-Weld Heat Treatment and Aging Post-Weld Heat Treatment on Tensile Test and Microstructure of Aluminium 6061 Weld Joint

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ABSTRACT

Aluminium 6061 is an aluminium composition with Al-Mg-Si alloy which is often used for offshore structure material due to its high strength, good ductility and good corrosion resistance as well as its mechanical properties that can be enhanced by heat treatment. The purpose of this paper is to show the effect of heat treatment variations, in the form of preheating and aging PWHT, on tensile strength and microstructure of aluminium 6061 welding connection with GTAW process using electrode ER 5356. The pre-heat temperature variations used were 80°C, 100°C, and 120°C and the aging PWHT temperature variations used were 180°C and 260°c. The result shows that specimen with preheat treatment temperature of 120°C and aging pwht temperature of 260°C had the largest ultimate strength of 246.74 MPa and yield strength of 125.21 MPa. The highest percentage of Mg2Si formed was also found on the same specimen with a percentage of 48.84% in weld metal, 58.75% in HAZ, and 43.54% in base metal.

Keywords: *AA 6061, preheating, aging heat treatment, Gas Tungsten Arc Welding*

1. INTRODUCTION

In recent years offshore industry has become increasingly interested in the use of lighter materials as it is considered to offer potential benefits in terms of reducing weight and the cost of offshore building production facilities. Aluminium alloy has received a lot of interest. Aluminium alloy provides some advantages compared to carbon steel in structural application, including combination of low density with moderate strength. In addition, it also has high corrosion resistance which reduce maintenance costs by eliminating the need for painting. According to [1] aluminium offers the greatest potential for weight and cost-saving on the topside structure area.

Aluminium alloy is divided into 2 groups, one that can be subjected to heat-treatment (heat treatable) and the others that cannot (non-heat treatable). 6XXX series aluminium is included in the heat treatable aluminium alloy because it contains Mg and Si[2], This series of aluminium is widely used for offshore industry including ship fabrication, oil and gas pipe, and offshore wind turbine. In manufacturing process of 6XXX series aluminium weld joint, it is advised to use Tungsten Inert Gas (TIG) and Metal Inert Gas (MIG) because its application is relatively easier and cheaper [3]. But in the process of welding, aluminium tends to undergo a change in dimension or distortion, because the residual voltage arising from the welding process will decrease the mechanical properties of the weld connection. In addition, aluminium is also prone to experiencing hot crack especially on aluminium-magnesium-silicon alloy [4].

The 6000 series Aluminium is an alloy that will respond when applied to heat treatment, therefore, to improve the mechanical properties of the welding of aluminium joints, heat treatment can be carried out. Heat treatments are preheating application before the welding process and aging post-weld heat treatment (PWHT). The purposes of preheating are to slow down the cooling rate, eliminate moisture and reduce the risk of crack [5]. The aging treatment can increase the strength of the material by forming Mg2Si precipitation with the right temperature [6].

To understand the effect of the application of preheating and aging PWHT against tensile strength and microstructure, this research will carry out single V joint of 6061 series aluminium alloy (AA6061) using Gas Tungsten Arc Welding (GTAW) with variation in the preheating temperature of 80°C, 100 °C and 120 °C and the variation in aging PWHT temperature of 180 °C and 260 °C.

2. MATERIALS AND METHOD

Several stages of research must be done, first step is to search for literature and references that are relevant to the research topic for example like books and journals. The next step is to design the welding procedure specification (WPS) based on variables that have been determined. Then prepare the material and tools for welding process, the welding process is based on the previously designed WPS. In this study the materials were given two kinds of heat treatment, preheating and post-weld heat treatment. Before welding, the materials are heated with temperature variations of 80°C, 100 °C and 120 °C. After weld joints were formed the materials are re-heated with temperature variations of 180°C and 260°C, this treatment called aging post-weld heat treatment. The final step is to convert the weld joint into a test specimen according to the chosen test standard, then to be applied to a mechanic test to obtain the joint strength and metallographic test to determine the macro structural behavior of the weld joint.

2.1 Alumunium 6061

The 6061 series aluminium alloy contains silicon and magnesium with a percentage of 0.4%-0.8% and 0.8%-1.2%, respectively. If the ratio of the content when fulfilling the required proportion of 1.73:1 for the formation of magnesium silicide (Mg2Si) so this alloy can carry out heat treatment [7]. The 6061 series aluminium alloy is the most versatile of the heat-treatable group that has good corrosion resistance and is commonly used in transportation and structural applications.

2.2 Gas Tungsten Arc Welding (GTAW)

Gas Tungsten arc welding (GTAW) is a welding process that uses an arc between tungsten electrodes (non-consumable) and welding points. This process uses shielding gas and without any applied pressure. This process can be used with or without the addition of metal fillers. The advantage of GTAW process is that it does not produce slag and spatter resulting in clean welding surface [8]. Metal fillers used to connect the 6061 series aluminium using GTAW process are ER 5356 and ER4043 [3]. The GTAW illustration can be seen in Figure 1.

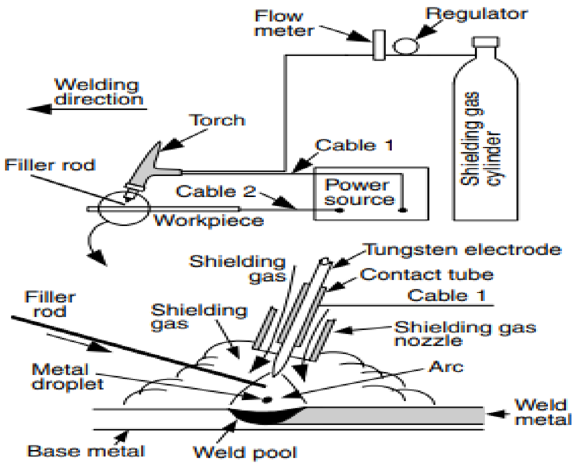

Figure 1. GTAW Welding Schemes [9]

2.3 Preheating

Preheating is a process of heating the material before the welding process takes place at a temperature under the recrystallization temperature. Preheating can use gas burner, oxy-gas flame, electric blanket, induction heating, or heating in the Furnace [10]. The main reason of preheating is slowing down the cooling rate on both welding metals and base metals, allowing hydrogen to be diffused to reduce potential cracks and improve the metal toughness [11].

2.4 Precipitation Hardening (Aging)

Precipitation hardening or strengthening of Precipitation is a process of heating aluminium alloy, this process consists of two steps, the alloy solution is heated between the solvus and liquidus line (between the temperature of 460 °c-540 °c) and held until homogeneous solid solution formed [12]. The solution process causes the alloy element to dissolve into a solid solution. The next process is quenching to keep the one phase alloy by cooling the solution quickly.

The next process is the aging, the alloy temperature is held at a certain point below the Solvus line for a certain time period. Aging process divided into two kinds, natural aging and artificial aging. Natural aging is an aging process of aluminium alloy that carried out in cold condition. Natural aging takes place at room temperature, between 15°C – 25°C and held for 5 to 8 days. Meanwhile, artificial aging is aging process of aluminium alloy that carried out in hot condition. Artificial aging takes place at temperatures between 100 °c-200 °c and held between 1 to 24 hours [13]. Artificial aging affects mechanical properties due to phase change in the microstructure [14]. Phase Diagram of the aluminium can be seen in Figure 2.

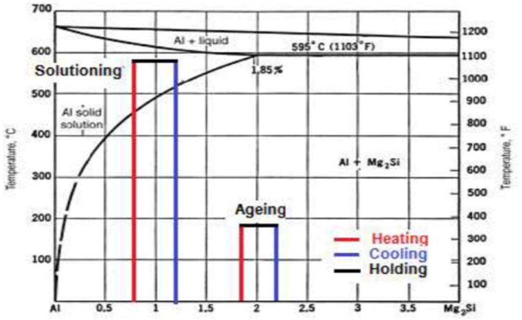

Figure 2. Alloy phase Diagram of aluminium Mg-Si [15]

2.5 Micro Test

Micro-testing is inspecting the structure of the material through enlargement using a special microscope for metallography. With microstructure testing, we can observe the shape and size of the metal crystals and support the result from tensile test. The micro-structure shot was taken on the weld metal, HAZ, and base metal. The result of the microstructure and mechanical properties is to identify the precipitation that occurs in the test material [16].

3. RESULT AND DISCUSSION

3.1 Welding Procedure

In this study, GTAW was carried out using the Welding Procedure Specification as follows:

Material Specification : Alumunium 6061
Dimensions : 300 mm x 150 mm x 6 mm
Joint Type : Butt Joint Single V
Welding Position : 1G
Filler Metal : ER 5356
Filler Metal (Dia.) : Ø 3.2 mm
Current Type : AC
Number of Layers : 3 Layers
Cleaning Method : Griding
Shielding Gas : Argon 99,99%
Gas Flow Rate : 15L/min, 20L/min and 25L/min
Preheating Temperatures : 80 °C, 100 °C and 120 °C.
Aging PWHT Temperatures : 180 °C and 260 °C

The illustration of groove specifications and specimen descriptions can be seen in Figure 3.

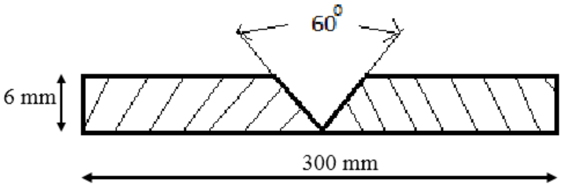

Figure 3. Joint Specification

Table 1. Specimen description

Specimen	Heat Treatment Temperature Variation
O	Non Heat Treatment
A1	Preheat of 80°C and Aging PWHT of 180°C
B1	Preheat of 80°C and Aging PWHT of 260°C
A2	Preheat of 100°C and Aging PWH of T 180°C
B2	Preheat of 100°C and Aging PWHT of 260°C
B2	Preheat of 100°C and Aging PWHT of 260°C
A3	Preheat of 120°C and Aging PWHT of 180°C
B3	Preheat of 120°C and Aging PWHT of 260°C

3.2 Tensile Test Result

Tensile testing was carried out to determine the effectiveness and behavior of a material when given an opposing force on the same axis located at both end of the specimen. Tensile testing was also used to determine the maximum strength that a material can withstand. The standard used in this test was AWS D1.2, where the welding specimen will be declared to have passed the tensile test if the ultimate strength of the weld metal exceeds the specified minimum limit. In this study, the acceptance criteria of AWS D1.2 code indicates that the minimum tensile strength of aluminium 6061 is 165 MPa. Each specimen was tested three times to get a valid result. Detailed test results of the seven test specimens can be seen in Table 2 - Table 8 with the visual result of the tested specimen in **Error! Reference source not found.** Figure 6, while for the test result's graph can be seen in Figure 7Figure 8.

Table 2. Non Heat treatment specimens Tensile Test Result

Specimen	Tensile Test Result			
	Yield Strength (MPa)	Ultimate Strength (MPa)	Average Yield (MPa)	Average Ultimate (MPa)
O1	88.16	167.81	87.73	167.66
O2	84.08	165.88		
O3	90.94	169.28		

Table 3. Specimens with preheat temperature of 80°C and aging pwht temperature of 180°C Tensile Test Result

Specimen	Tensile Test Result			
	Yield Strength (MPa)	Ultimate Strength (MPa)	Average Yield (MPa)	Average Ultimate (MPa)
A1.1	88.81	186.98	90.85	186.70
A1.2	90.94	185.59		
A1.3	92.79	187.53		

Table 4. Specimens with preheat temperature of 100°C and aging pwht temperature of 180°C Tensile Test Result

Specimen	Tensile Test Result			
	Yield Strength (MPa)	Ultimate Strength (MPa)	Average Yield (MPa)	Average Ultimate (MPa)
A2.1	111.36	204.06	111.80	203.85
A2.2	113.45	201.85		
A2.3	110.58	205.65		

Table 5. Specimen with preheat temperature of 120°C and aging pwht temperature of 180°C Tensile Test Result

Specimen	Tensile Test Result			
	Yield Strength (MPa)	Ultimate Strength (MPa)	Average Yield (MPa)	Average Ultimate (MPa)
A3.1	120.10	222.64	120.48	220.94
A3.2	118.73	220.43		
A3.3	122.62	219.74		

Table 6. Specimens with preheat temperature of 80°C and aging pwht temperature of 260°C Tensile Test Result

Specimen	Tensile Test Result			
	Yield Strength (MPa)	Ultimate Strength (MPa)	Average Yield (MPa)	Average Ultimate (MPa)
B1.1	121.29	217.22	117.35	215.62
B1.2	116.54	213.85		
B1.3	114.21	215.78		

Table 7. Specimens with preheat temperature of 100°C and aging pwht temperature of 260°C Tensile Test Result

Specimen	Tensile Test Result			
	Yield Strength (MPa)	Ultimate Strength (MPa)	Average Yield (MPa)	Average Ultimate (MPa)
B2.1	120.36	230.43	119.88	228.07
B2.2	119.45	226.60		
B2.3	119.83	227.17		

Table 8. Specimens with preheat temperature of 120°C and aging pwht temperature of 260°C Tensile Test Result

Specimen	Tensile Test Result			
	Yield Strength (MPa)	Ultimate Strength (MPa)	Average Yield (MPa)	Average Ultimate (MPa)
B3.1	127.53	249.68	125.21	246.74
B3.2	122.24	247.82		
B3.3	125.86	242.73		

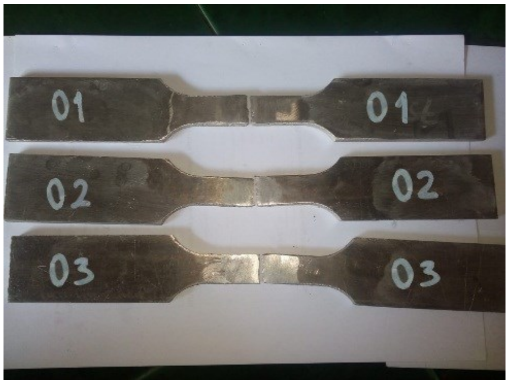

Figure 4. Non Heat Treatment Specimens Tensile Test Result

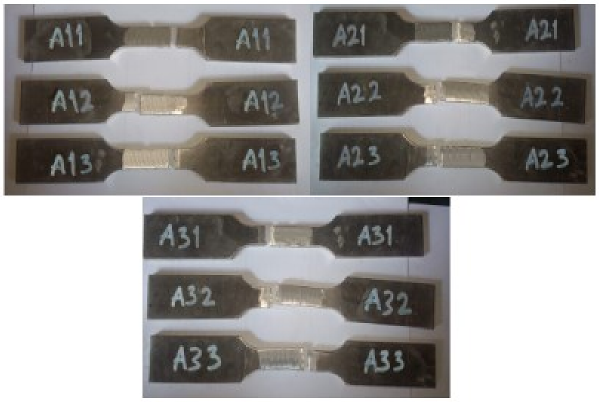

Figure 5. Specimens with Aging pwht temperature of 180°C Tensile Test Result

Figure 6. Specimens with Aging pwht temperature of 260°C Tensile Test Result

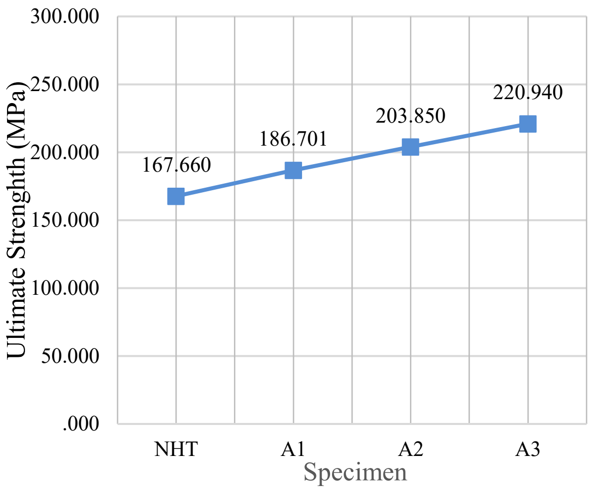

Figure 7. Graph of Tensile Test Result on Aging pwht temperature of 180°C

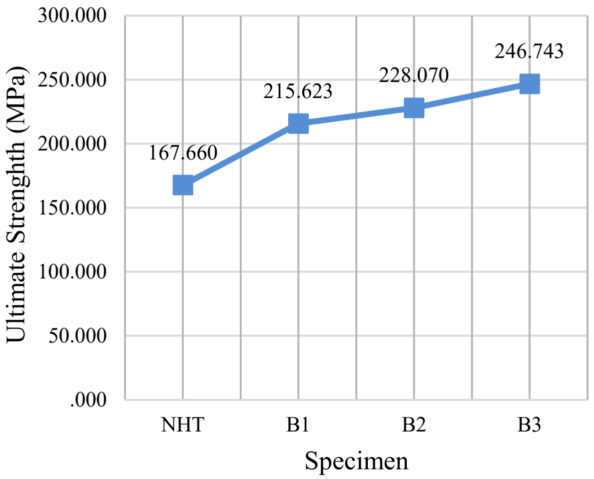

Figure 8. Graph of Tensile Test Result on aging pwht temperature of 260°C

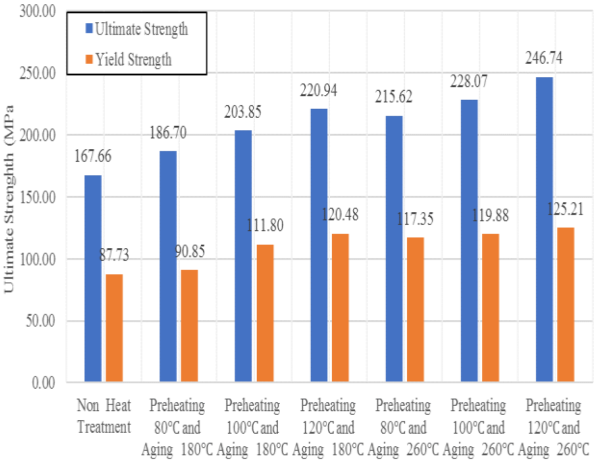

Figure 9 Tensile test result

The ultimate strength obtained in all seven specimen indicates that the results of the tensile test have exceeded the standard, meaning that all specimens passed the tensile test. Based on the graphs in Figure 7 and Figure 8, it can be seen that the use of different aging temperature shows the same trendline, that is increasing the preheat temperature will result in increased tensile strength. According to [17], preheat application can increase the strength and toughness of welding results and reduce the risk of crack. In Figure 13, the chart shows that by increasing the aging temperature, the tensile strength will also increase, the same results were obtained in research conducted by [18]. It can be concluded that preheat treatment and aging PWHT affected the tensile strength of the material. With preheat temperature of 80 °C and aging temperature of 180°C, tensile strength increased by 10,2%, at preheat temperature of 80°C and aging temperature of 260°C, tensile strength increased by 22,24%, at the preheat temperature of 100°C and aging temperature of 180°C tensile strength increased by 17,75%, at preheat temperature of 100 °C and aging temperature of 260°C, tensile strength increased by 26,48%, at preheat temperature of 120°C and aging temperature of 180°C, tensile strength increased by 24,12%, and the highest tensile strength obtained at preheat temperature of 120 °c and aging temperature of 260 °C, with the tensile strength increasement reached 32,05%.

3.3 Micro Test Result

In the photo of the microstructure, that were obtained using an electron microscope with 100x magnification. The areas observed in microstructures were weld metal, HAZ, and base metal on each specimen. The results of the micro photograph showed 2 areas that represent each phase. According to [19] the bright area (white) on 6061 series aluminium alloy photograph was a solid solution (α) phase, while the dark area (black) was Mg2Si phase. The existence of Mg2Si affects the mechanical strength of the aluminium.

The observation of microstructure obtained that in the welding without any heat treatment applied, dendritic and eutectic microstructures could be found in the area of weld metal, and heat affected zone (HAZ). Meanwhile, the base metal microstructure did not have significant change. On the 6 specimens that were given heat treatment, specimens A1, A2, A3, B1, B2, and B3, microstructure changes could be found in the weld metal, HAZ, and base metal. As the aging temperature increased, the grain size looks more refined and more Mg2Si particles can be found and evenly distributed. Micro testing showed that the highest Mg2Si percentage could be found on specimen B3 with preheat temperature of 120°C and aging PWHT temperature of 260 °c, which were 48.84% in weld metal, 58.75% in HAZ, and 43.54% in base metal. This indicates that Mg2Si phase will increase in number along with the increase in preheat and aging PWHT temperature. The percentage value of both phases in each specimen can be seen in Table 9 and the microstructure image can be seen in Figure 10Figure 16.

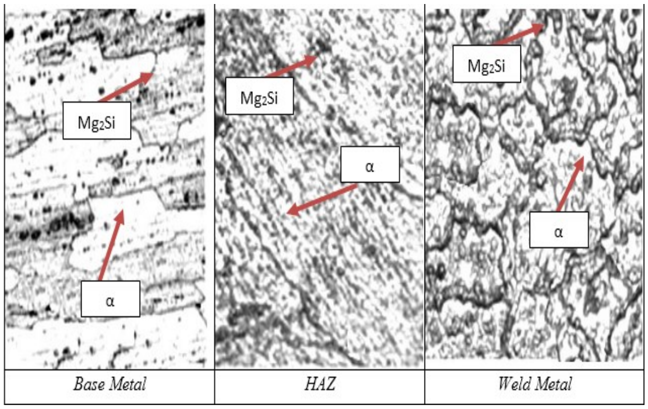

Figure 10 Microstructure Result of NHT Specimen

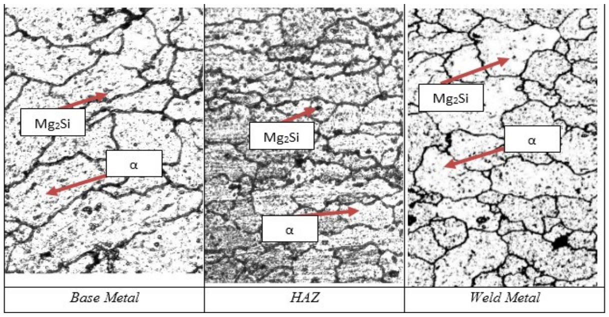

Figure 11 Microstructure Result of A1 Specimen

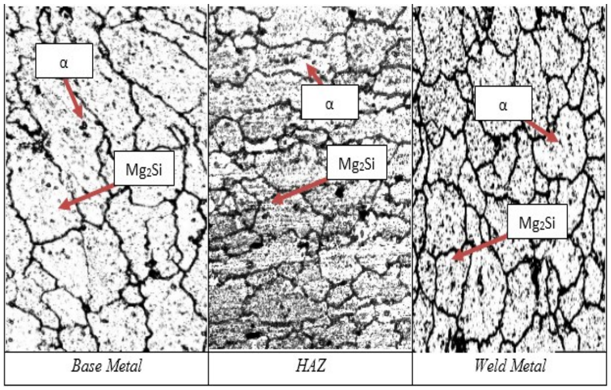

Figure 12 Microstructure Result of A2 Specimen

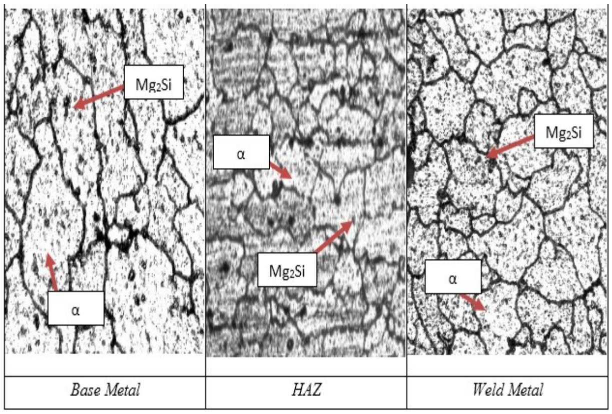

Figure 13 Microstructure Result of A3 Specimen

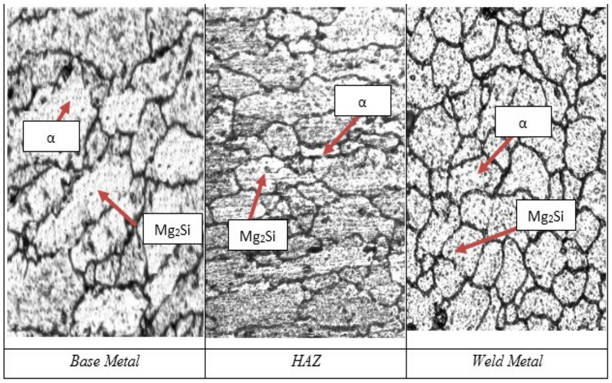

Figure 14 Microstructure Result of B1 Specimen

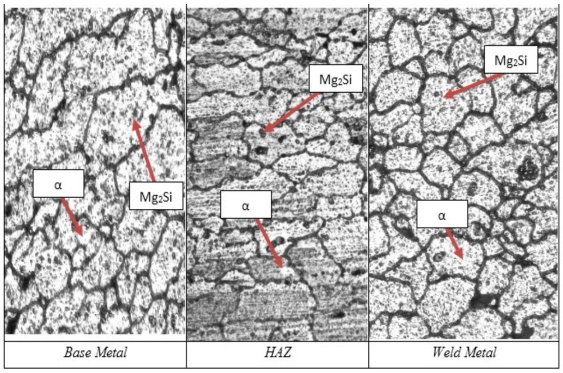

Figure 15 Microstructure Result of B2 Specimen

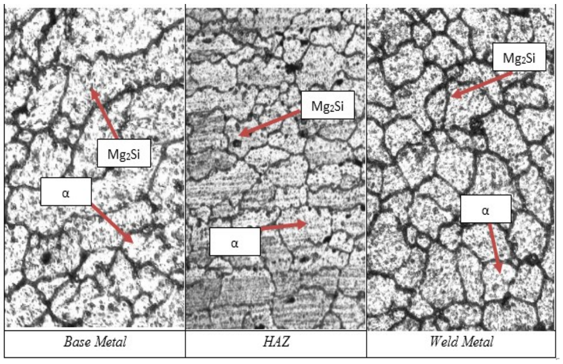

Figure 16 Microstructure Result of B3 Specimen

Table 9 The result of micrtostructure test

Specimen	Base Metal		HAZ		Weld Metal		Average	
	Alpha	Beta	Alpha	Beta	Alpha	Beta	Alpha	Beta
NHT	70.65%	29.35%	64.03%	35.97%	68.16%	31.84%	67.61%	32.39%
A1	62.56%	37.44%	49.75%	50.25%	59.35%	40.65%	57.22%	42.78%
A2	61.15%	38.85%	49.45%	52.51%	57.62%	42.38%	56.07%	44.58%
A3	60.21%	39.79%	47.49%	53.21%	56.75%	43.25%	54.82%	45.42%
B1	58.72%	41.28%	43.68%	56.32%	53.86%	46.14%	52.09%	47.91%
B2	57.62%	42.38%	43.15%	57.85%	51.87%	48.13%	50.88%	49.45%
B3	56.46%	43.54%	41.25%	58.75%	51.16%	48.84%	49.62%	50.38%

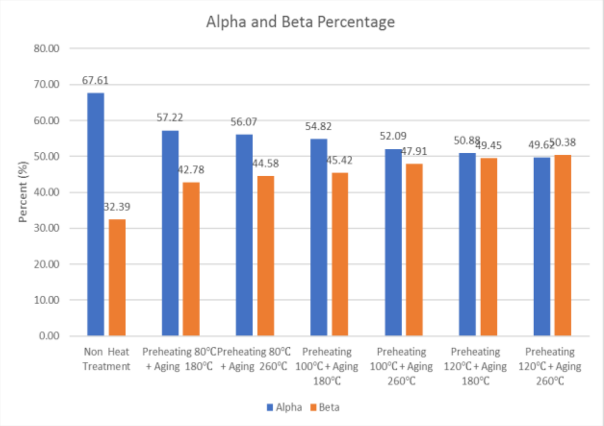

Figure 17 Graph of average alpha and beta

3.4 The Relationship between Tensile Test and Metallographic Test

From the tensile test and micro observation that have been carried out, it is clear that the application of heat treatment can greatly affect the welding result. Figure 13 shows that the highest tensile strength can be found in specimen B3 with preheat temperature of 120 °C and aging PWHT temperature of 260 °C. Tensile strength increasement reaches 30,28%, this is due to the high number of Mg2Si phases, this also supported by the result of micro-test that indicates the highest Mg2Si percentage can be found on specimen B3. Mg2Si has high toughness and tensile strength properties that increase the tensile strength. In addition, the grain size of the B3 specimen was also smaller, resulting in increased grain boundaries so that dislocation hardly occurred and higher tensile strength obtained. Without heat treatments, the specimen's tensile strength was low due to a small number of formed Mg2Si.

In all seven specimens, the breaking point was found in base metal, this was supported by the results of micro tests. The lowest percentage of Mg2Si was found on the base metal. Moreover, the base metal had coarser and bigger grain so that it became not only the weakest area among the three weld areas, but also the location of breaking point. It can be concluded that the increase in the preheat and aging pwht temperature are directly proportional to the number of formed Mg2Si and grain size of the microstructure, resulting in increased tensile strength of the materials.

4. CONCLUSION

From this research, the effect of variations in preheating temperature of 80°C, 100°C, and 120°C, as well as aging Post-weld Heat Treatment temperature variations of 180°C and 260°C using the GTAW process on joining the Alumunium 6061 series could be observed. Three points were elaborated as follows:

1. The highest tensile strength can be found in the specimen with the highest preheat and aging pwht temperatures of 120oC and 260oC, respectively, with the ultimate strength of 246,7 MPa and the yield strength of 125,21 MPa.
2. The application of preheating and aging PWHT increased the ultimate strength value of 10.2% in specimen A1, 22.24% in specimen B1, 17.75% in specimen A2, 26.48% in specimen B2. 24.12% in specimen A3, and 32.05% in specimen B3.
3. In microstructure observation, higher preheat and aging PWHT temperature will increase the amount of Mg2Si. The highest Mg2Si percentage can be found on specimen with preheat temperature of 120°C and aging pwht temperature of 260°C, with 48.84% in weld metal, 58.75% in HAZ, and 43.54% on base metal.

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