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Microstructural Evaluation for TIG Welding of AA6061-T6 using ER5356 Filler Metal; in Postweld and as-Weld Treatment

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ABSTRACT: AA6061-T6, as a heat treatable alloy, is a sensitive alloy to any thermal cycle. Heat can be imposed to AA6061-T6 during tungsten inert gas welding (TIG) and the microstructure of alloy can be affected subsequently. The purpose of this study is to evaluate the microstructure of as-weld and postwelded samples. Heat affected zone (HAZ) in two different temperatures (solution and aging temperature) in as-weld sample was revealed. Microstructure and hardness were restored in AA6061-T6 by applying post weld heat treatment (PWHT), however, liquid cracking (LC) was found in partial melted zone (PMZ). Whereas filler metal-ER5356- was not a heat treatable alloy, however, its microstructure was changed from a dendrite one to equiaxed grains with closed boundaries and displayed higher hardness from (60) HV to (80) HV due to the post weld heat treatment (PWHT).

KEYWORDS: Aluminum alloy, AA6061-T6, ER5356, microstructure, post weld heat treatment and liquid cracking.

INTRODUCTION

Aluminum alloys and components have been highly used in many industrial applications with a significant pace and accordingly several research works that concern these alloys have been established over the time. One of the important research fields for aluminum alloys is in joining processes [1]. These alloys have been categorized in heat treatable and non-heat treatable alloys. By noticing the development in the application of Heat treatable aluminum alloys in the welding industry, they have been subjects of specific investigation for their welding behavior due to softening in heat affected zone of weld. Among heat treatable groups, 6XXX are widely used for many applications such as shipbuilding, design of armor structures, marine structures, aerospace, and automotive industries because of their special properties such as high strength to-weight ratio, plasticity, ease in joining and good corrosion resistance. Whereas AA6061-T6 is one of the most common alloy in this group [1,2].

For joining of this alloy and considering the technical and economic parameters, tungsten inert gas welding (TIG) has been frequently applied to weld aluminum alloys. As a matter of fact, (TIG) welding is the most common traditional technology for AA6061-T6 welding [3].

On the other hand, propensity of the weldment to overage is the main issue related to (TIG) welding of AA6061-T6 aluminum alloy, which leads to weakening in its metallurgical properties in (HAZ). The thermal cycle imposed by welding and consequence of the cooling rate (after welding) in parent metal lead to inhomogeneous heating and cooling. This variation in the joint creates the so-called heat affected zone (HAZ). The heat can pose detrimental effects on the microstructural properties of AA6061-T6 [2,3].

In addition to weld zone which is usually formed from 4XXX or 5XXX aluminum alloys as filler metals, Heat Affected Zone- HAZ has two subzones. The first one is near to the weld zone, which is exposed to solution temperature (530-570 °C) and second is the subzone close to base metal, which experiences overaging temperature (100-300 °C). The results show the precipitation coarsening in (HAZ). The well-known reaction that happens in second subzone is where the discontinuous (Mg2Si (β)) phase is made after replacement from semi cohesive needles (β′) and rods (β″) Mg and Si mixture [3-5]. It means, in (TIG) welding, in addition to microstructural issue in weld zone, the precipitation and grain growth in (HAZ) have huge influence in the microstructural properties of joint.

For welding material, (4043) and (5356) rod fillers are most in demand. (5356) with (5) % Mg is stronger and more ductile than (4043), while (4043) containing (5) percent silicon and better flowing is more crack-resistant and easier to weld with. Although the hot crack can be seen in dilution area of (5356) and AA6061, the better mechanical properties could be achieved by this filler metal [6,7].

Post weld heat treatment (PWHT) can be applied to restore microstructure and mechanical properties of AA6061-T6. The importance of (PWHT) has concerned many researchers when the filler metal (5356) is not a heat treatable one.

This work emphasizes on microstructure of different zones in (TIG) welding of AA6061-T6 as well as mechanical properties (hardness) in as-weld and (PWHT) conditions. The special attention was done on microstructure of weld zone (WZ).

MATERIALS AND METHOD

Materials and Welding

AA 6061 includes Mg-Si-Al alloying elements. The parent alloy was a wrought 6061-T6 aluminium alloy plate. Table 1. and Table 2. show the nominal composition as well as mechanical properties of the base metal used in this study.

Table 1. Nominal Chemical Composition of Materials Used In This Research.

Material	Si	Mg	Cu	Fe	Mn	Zn	Al
AA6061-T6	0.60	0.90	0.31	0.33	0.07	0.03	Balance

Table 2. Mechanical properties of the 6061-T6 aluminium alloy used in this work.

Yield strength (MPa)	Ultimate strength (MPa)	Elongation (%)	Hardness (HV)
270	308	13.8	104

Two plates that were cut in (300 x 150 x 6) mm dimensions, were fabricated in a butt joint single V (one side bevel) with a bevel angle of (70°). The joint design “Figure 1” was welded with a (ER5356), Table 3. filler metal in three passes. The diameter of filler metal is (1.6 mm). Two passes welding in one side (root pass and filling pass) and one back welding pass after grinding probabilistic flaw of first or root pass were performed. (TIG) welding parameters can be seen in Table 4. Whereas, first pass as a root pass needs the highest current due to maximum dilution during welding process.

Table 3. Nominal chemical composition of materials used in this research.

Material	Si	Mg	Cu	Fe	Mn	Zn	Ti	Al
ER5356	0.08	5.09	0.22	0.30	0.10	0.11	0.16	Bal

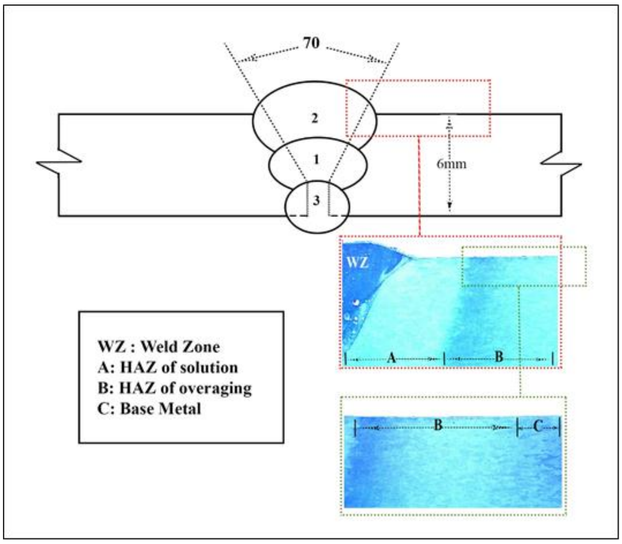


Figure 1. Schematic of fabrication and macrostructure of as-weld sample of this work; HAZ, WZ and Base Metal.

Table 4. welding parameters.

Layers	Process	Filler Metal	Filler Metal	Electrical			Travel Speed Range
		Class	Diameter	Type & Polarity	Current Range	Voltage Range	
1	TIG	ER 5356	1.6	DCEN	160-180	16-22	10-12 CM/MIN
2	TIG	ER 5356	1.6	DCEN	140-160	18-22	12-15 CM/MIN
3	TIG	ER 5356	1.6	DCEN	140-160	18-22	12-15 CM/MIN

Post Weld Heat Treatment (PWHT)

To assess the influence of heat treatment on the microstructure and mechanical properties of joints, PWHT was done on the welded samples. The heat treatment procedure was conducted according to what comes from metals handbooks (Vol. 4, Heat Treating) [8], as shown in "Figure 2".

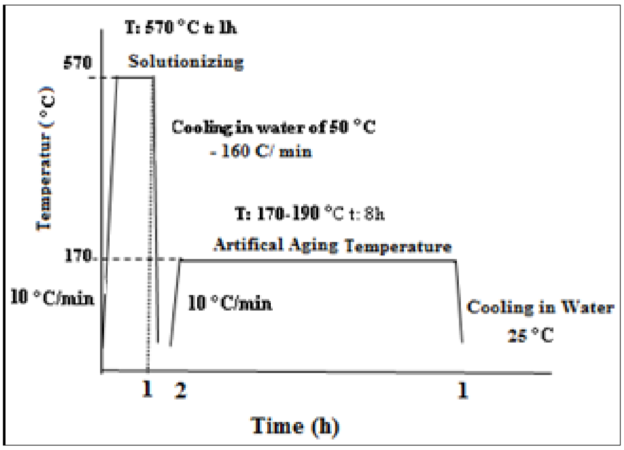


Figure 2. T6- heat treatment cycle performed on the TIG samples [8].

Microstructural Evaluation

For finding a different zone in (HAZ) and other zones of joints, first of all, hardness measurement was carried out on the cross section upright to the weld direction by using a square-base diamond pyramid indenter (microhardness Vickers) at a load of (500) g at every (2) mm (on a line from center of weld zone(WZ) along the center of plate) while the dwell time was (10) s.

For microstructural investigation, as-weld and (PWHT) samples were grinded and polished by wet-grinding applied (SiC) papers in different grits (400, 600, 800, 1200 and 2000), followed by burnishing with (1) μm diamond past, degreased by acetone, washed with distilled water, and finally dried. In order to reveal the recognized microstructure, according to (ASTM) standard E340 [9], samples were immersion in a appropriate solution for etchant which composed of (25) ml (HNO3), 13 ml (HCl), 2 ml (HF), and 60 ml (H_2O) for 2 min, washed immediately with distillate water, dried in a cold stream of air. In the following, the different microstructures of weldment were studied and observed by an Olympus light microscope. FESEM (Nova SEM 230) with (EDS) was also applied for analyzing the microstructure of the samples.

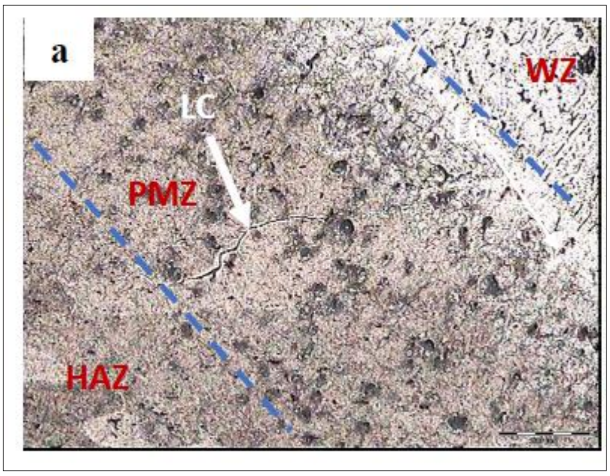
RESULTS AND DISCUSSION

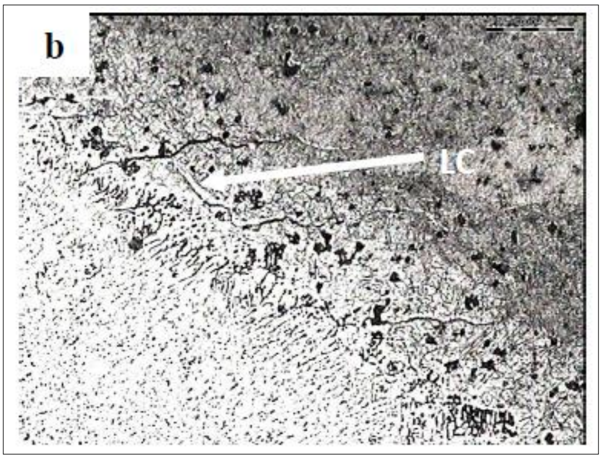
Macrostructure and Partial Melted Zone (PMZ)

Macrostructure of the as-weld joint including welding zone (WZ), dilution line (weld and base metal interface) and (HAZ) which is seen in brighter color or A (resulted in solution temperature) and darker color or B (resulted in aged temperature-overaged) are shown in “Figure 1”. Microhardness measurement needs to be used for highlighting an accurate extent of these two kinds of (HAZ).

However, after (PWHT), some macroscopic (and microscopic) alterations can be seen around the dilution area of weld metal and parent metal, so-called partial melted zone (PMZ). In partial melted zone (PMZ), the temperature of the material is raised above the eutectic temperature. In this case the temperature is raised above the solidus temperature which the work piece is solutionized. “Figure 3”, specifies the liquation cracking

(LC) in partial melted zone (PMZ). Liquation cracking occurs mostly along the grain boundaries in (HAZ) [6,7].





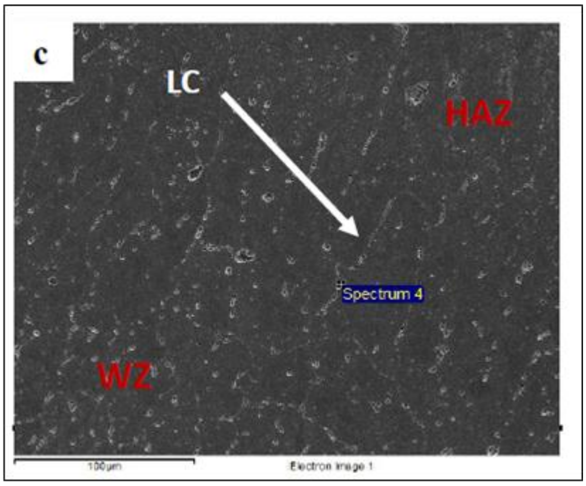


Figure 3. Liquation cracking (LC) (a) after PWHT (b) as-weld (c) EDX of LC.

Table 5. Illustrate the percentages of liquation cracking (EDX) of LC.

No.	Element	Weight%	Atomic%
1	Mg K	2.64	2.92
2	Al K	97.36	97.08
Total		100%	

Table 5. Percentages of liquation cracking EDX of LC.

What can affect the liquation cracking susceptibilities are temperature range and composition in the base material and filler metal. The weld metal composition is resulting from a mixing between the base metal and the filler metal. The dilution ratio is a mixing level of the filler metal and base metal in the welding pool. (TIG)-welding of alloy AA6061 with filler metal AA5356 (Al/Mg) at a high dilution ratio can cause liquation cracking [7].

Doing solution in (PWHT) and existence of (Mg/Al) components with different thermal coefficient compare to matrix are the main reasons for liquation cracks in these samples. However, LC has also been found in as-weld samples in “Figure 3B”, and “Figure 3C”, shows a (FESEM) image of (PMZ) and LC and also (EDX) analysis of a point in LC can be seen in “Figure 3C”.

Microhardness

“Figure 4”, shows micro hardness tests were carried out along the central line of the weld in as-weld and (PWHT) samples. As already mentioned, the (HAZ) in (TIG) welded joints of heat treatable aluminum alloys are included 2 parts (including solution area and over aging area). The minimum hardness belongs to over aging division in (HAZ) of as-weld sample with (38) HV hardness. Whereas the minimum in (PWHT) is almost (78) HV in (WZ). It means that (PWHT) can efficiently return this property.

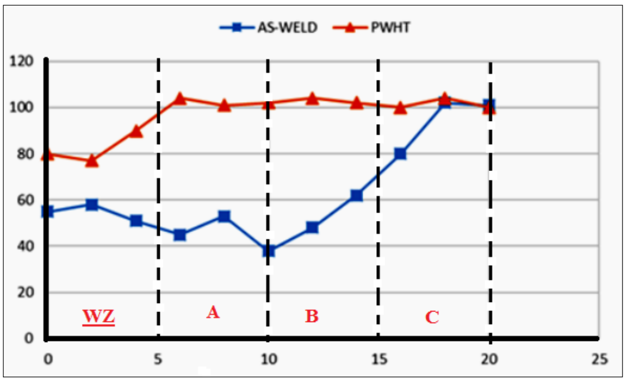


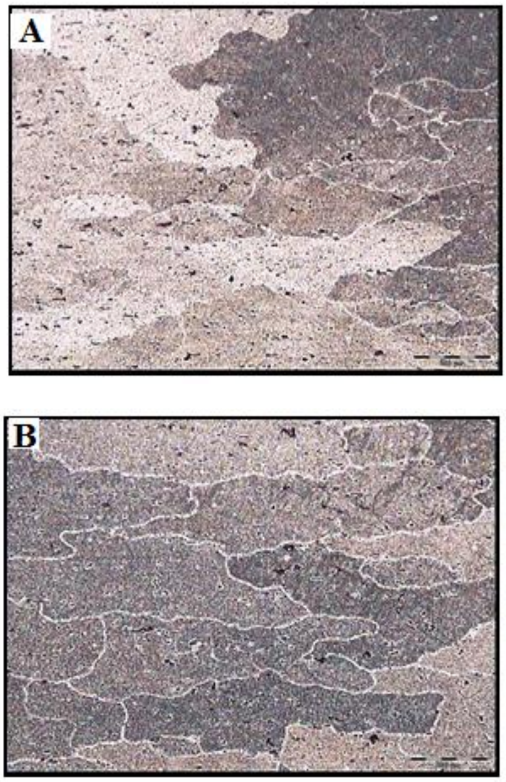
Figure 4. Microhardness of As-weld and PWHT samples (WZ, A, B and C are in agreement with Figure 1).

The filler metal is (5356), though. In this non-heat treatable filler metal, hardness was changed from 60 HV to 80 HV in as-weld and (PWHT) consequently.

Microstructure Evaluation

HAZ is displayed in “Figure 5”. Whereas “Figure 5A” shows the (HAZ) in as-weld sample which is close to the weld region that experienced higher temperature (solution temperature). Thicker grain boundaries that are caused from immigrated depositions (due to solution of deposition) are pointed in light lines in this picture. On the other hand, over aged division is seen in figure 5b which indicates thinner or no grain boundaries in some areas. It also shows greater second phases due to precipitation coarsening [2,4,10]. The transformation from (β″) to (β′) and finally β (Mg2Si) precipitates occurred because of an extensive and frequent thermal cycle of (TIG) welding. These results are regular with the earlier studies published by researchers [2,4].

Restored (HAZ) microstructure after (PWHT) can be seen in “Figure 5C”.



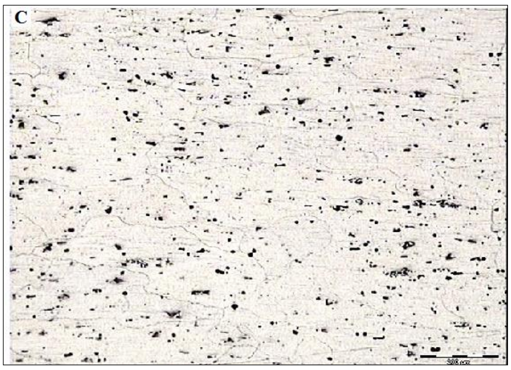


Figure 5. Optical microstructure of HAZs, a) HAZ of solution area, b) HAZ of overaged area, c) HAZ after PWHT.

The dendritic microstructure is formed in the center of (WZ) of as-weld sample “Figure 6”. The main reasons for this nonstructural texture are high solidification and cooling rate, although, our welding procedure had a preheat. Previous studies that used (Mg) rich filler metals in welding of aluminum alloys stated this type of microstructure [11,12].

Figure 6. Optical microstructure in WZ of as-weld.

“Figure 7”, displays equiaxed grains with closed boundaries. ER5356 is not considered as a heat treatable alloy, though, (T6) heat treatment as a postweld heat treatment for the weldment has completely transformed microstructure of the weld zone (WZ), where an interconnected grain boundary was formed. High amounts of (Mg) in this boundaries “Figure 8” is reported in the findings of Choi et al. [12] and Scamans et al. [13,14]. These works have highlighted the presence of (Al3Mg2) at grain boundaries. The black points inside the grains of “Figure 7” are the compositions (precipitations) of (Al/Mg) elements as well as the white points of “Figure. 9”. By looking at binary diagram of (Al-Mg) in “Figure 10”, all (Al3Mg2) can be dissolved in solution temperature of AA6061-T6 and be emerged under (450° C) (Aging temperature is about (170 $^{\circ}$ C). It means (PWHT) can represent (Al3Mg2) intermetallic on grains as boundaries as well as precipitations inside the grains [6,7,15-21].

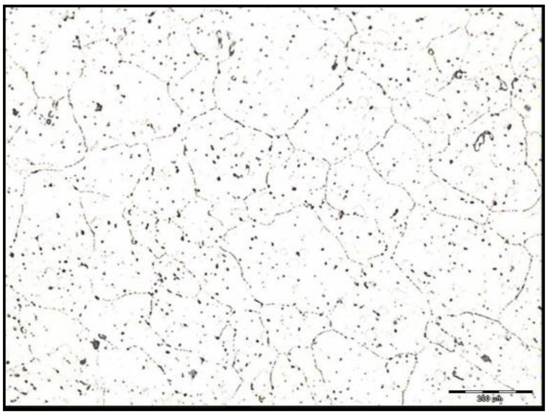
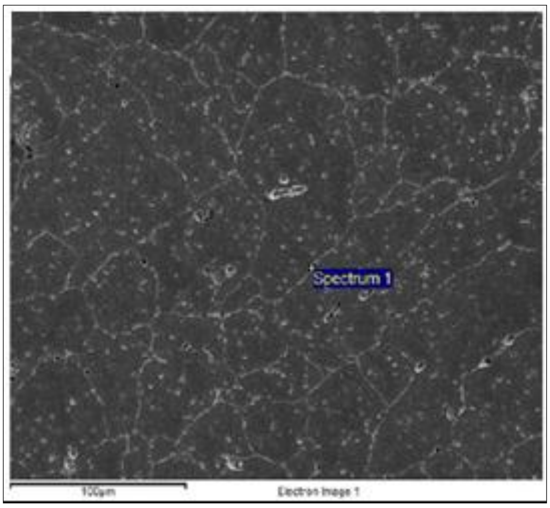
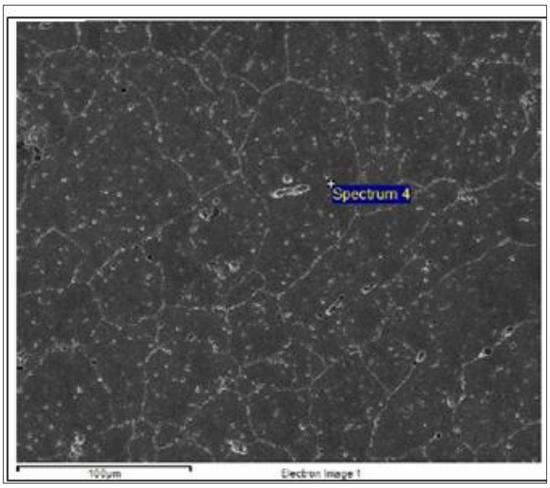


Figure 7. Optical microstructure of weld zone after PWHT.



Element	Weight%	Atomic%
Mg K	4.24	4.68
Al K	95.76	95.32
Totals	100.00	

Figure 8. FESEM of WZ after PWHT, [EDX analysis of grain boundary]



Element	Weight%	Atomic%
Mg K	3.27	3.61
Al K	96.73	96.39
Totals	100.00	

Figure 9. FESEM of WZ after PWHT, [EDX analysis of the white points inside the grain].

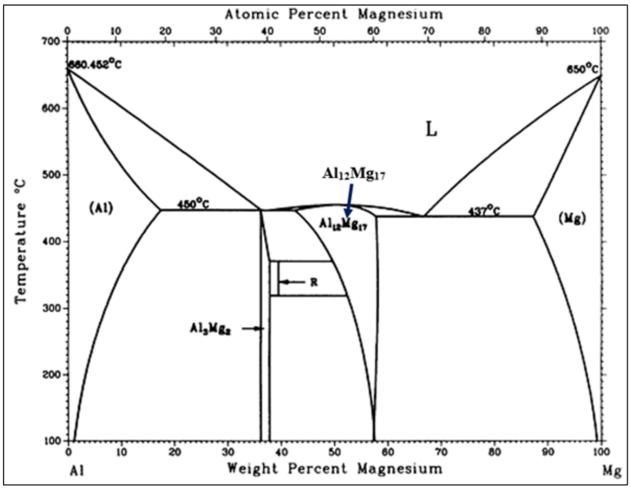


Figure 10. Al-Mg binary phase diagram [17].

CONCLUSION

1- LC occurred in PMZ due to (Mg/Al) components with different thermal coefficient compare to matrix in (PWHT) sample.

2- As-weld sample has 2 minimum hardness points in (HAZ) because of solution temperature close to (WZ) and overaging temperature in a little further distance

3- Hardness was returned in AA6061-T6 by using (PWHT).

4- A closed net structure (equiaxed grains with closed boundaries) was appeared in (WZ) after (PWHT). Whereas the (5356) is not a heat treatable aluminum alloy.

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