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Microstructure and Mechanical Properties of TIG-Welded AA6061-T6 Joints after Solution Treatment and Artificial Aging at Different Temperatures

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ABSTRACT

Aluminum AA6061-T6 alloy has good strength and is widely used in mechanical engineering. In practice, a similar joint using a fusion welding process can reduce strength in the weld metal, heat-affected zone, and base metal regions. The purpose of this study is to investigate the effect of artificial aging temperature on the microstructure and mechanical properties of the AA6061-T6 joints. Similar joints were prepared using Tungsten Inert Gas (TIG) welding with ER 4043 filler metal and argon gas as shielding. The microstructure observation was performed using an optical microscope (OM). Vickers hardness, universal testing machine (UTM), and three-point bending test were carried out to investigate the mechanical properties of similar AA6061-T6 joints. The result shows that the weld metal (WM) and heat-affected zone (HAZ) areas have finer grains than the base metal (BM). Introduction of artificial aging with different temperatures promoted the strength improvement compared to the as-welded AA6061. The temperature of 155 °C showed higher hardness, increasing by more than 100% in the HAZ area. Furthermore, the maximum ultimate tensile strength of 201.4 MPa was obtained at an artificial aging temperature of 185 °C. On the other hand, the bend test shows an acceptable condition at an artificial temperature of 155 °C at the root area. Based on the data, it can be concluded that the artificial aging temperature strongly influences the microstructure evolution and mechanical properties of welded AA6061-T6.

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1. INTRODUCTION

Recently, welding technology has developed significantly and has been applied in various ferrous and non-ferrous materials, such as metal active gas (MAG) welding applied to steel (Yana et al., 2025), the MIG method used to join Al 1100 (Bintoro et al., 2024), and Al-Mg-Mn alloys have been successfully joined using TIG (Alzahrani et al., 2025). Particularly, gas tungsten arc welding (GTAW) or tungsten inert gas (TIG) welding is widely used in the welding area. Its precise control of process parameters makes it a promising joining technique in varying aluminum alloys. The aluminum AA1135 was successfully joined by GTAW with different welding currents (140, 160, and 180 A), in which a significant difference in hardness at the HAZ and weld metal was obtained (Suherman et al., 2023). The heat input also influences the hardness of the 2A14 aluminum weld joint; the excessive value is detrimental to the hardness (Zhao et al., 2022). Furthermore, the joining of the AA6061-T6 can also be done by using GTAW, in which the full welding shows better mechanical properties than a single-pass process (Ji et al., 2023). The TIG welding results are strongly influenced by their process parameters. Al Kareem S.A. et al. proposed that the welding currents (90, 95, and 100 A) are significantly more influential than the other parameters (welding speed and gas flow) in the hardness of AA6061-T6 weld metal, a different hardness is still observed in the HAZ area (Al Kareem et al., 2023). The welding current within 120-160A was applied in joining the AA6061-T6 material, in which 160 A current and ER 5356 electrode resulted in higher hardness (WM area) and weld metal strength, but low strain (Azwinur & Syukran, 2021). It is believed that TIG welding offers precise control and high-quality welds. Despite these advantages, the higher heat input from the GMAW process could promote grain coarsening and welding defects, which finally reduce the strength (Riswanda et al., 2024).-The presence of defects and cracks was located at the fracture location in the weld metal (Xu et al., 2023). Grain coarsening can be formed due to high heat input during the welding process, which weakens the strength of the weld metal (Shafeek et al., 2024). Furthermore, restoring the properties of weld metal can be done through the post-weld heat treatment (PWHT) process.

The PWHT process such as artificial aging, has the potential to be used to restore the microstructure and improve the mechanical strength of the weld metal. Solution treatment followed by artificial aging at temperatures ranging from 150 to 250 °C increases the hardness of AA7075-T6 aluminium alloy, the highest hardness 81,7 HV obtained by 250 °C and 22 h holding times, in which the increase in hardness correlated with precipitate formation (Naafila et al., 2024). The aging process was also applied in the AA6061-T6 with aging temperature of 140, 160, and 180 °C, this process was conducted without solution treatment (Phan et al., 2026). This solution treatment plays an important role in the grain growth and complete dissolution of the 2024 aluminum alloy, the increase in solution temperature from 480 °C to 550 °C tend to increase the hardness (Zhang et al., 2025). Furthermore, the aging process facilitates precipitate formation and increases hardness (Zhang et al., 2024). The precipitate θ′-Al2Cu formed in the microstructure of the AA2219 alloy contributes to the strength improvement, in which the precipitate was generated at 175 °C temperature for 12 h (Zhu et al., 2025). The 4xx.x aluminum type shows the strength improvement through artificial aging at temperatures of 190-210 °C for 60-minute holding times (Edo Revianto & Susiana, 2021). The precipitates evolution in the AA6061-T6 alloy with increasing temperature and holding times within (160, 180, and 190) °C and (60, 10, and 5) h holding times occurred, respectively (Polat et al., 2015). The temperature parameter at 180 °C significantly enhances hardness, with a maximum of 110.9 HV obtained for AlSiMg aluminum alloys (Andoko et al., 2020). Besides temperature, holding time also contributes to improved characteristics. A holding time of 4 h and 155 °C enhances the hardness of Al-Si-Cu-Fe alloys as reported (Shieddieque & Kuswandi, 2025). Artificial aging of 6063 Aluminum at 180 °C for 0.5 to 8 h was carried out, during which the hardness increased with increasing holding time up to 8 h (Li et al., 2023). However, the increase of holding times potentially reduces the hardness of aluminum alloy, this phenomenon occurred at the AA6061 alloys from 1 to 5 hours at 150 °C of artificial aging temperature (Pradityana & Kurniawan Widyantoro, 2019).

The study of artificial aging on the aluminum alloys and its effect on the characteristics of welded metal attracted many researchers. Based on previous studies, artificial aging was conducted at varying temperatures and holding times. The investigation on the systematic role of 155, 185, and 215 °C temperature with an 8 h holding time remains scarce. This current study addresses this gap by investigating the microstructure evolution and mechanical properties of AA6061-T6 weld material. Furthermore, this work provides novel insights into optimizing these specific temperature parameters for the characteristics of aluminum welding. This current study aims to investigate microstructure evolution in the weld metal and heat-affected zone (HAZ) area. The correlation of different holding times and hardness, tensile strength, and bending strength was investigated. Furthermore, this research provides a technical framework for optimizing the post-processing of AA6061-T6 welds in industrial applications. In practice, this study provides welding engineers with a precise post-weld heat treatment parameter to obtain better joint efficiency.

2. RESEARCH METHODS

The experimental study on the effect of artificial aging at different temperatures on the characteristics was carried out with the AA6061-T6 as the starting material, the composition of this material as shown in Table 1. Furthermore, the selected filler metal in this study was chosen based on the base metal composition, in which ER 4043 type (Table 1) has been used.

Table 1. Composition of base metal AA6061-T6 and filler ER 4043

Elements	Zn	Mg	Cu	Fe	Mn	Si	Cr	Be	Ti	Al
AA6061-T6	0.03	0.92-0.99	0.18-0.23	0.27-0.3	0.05	0.48-0.55	0.1	-	-	bal.
ER 4043	0.1	0.05	0.3	0.8	0.05	4.5-6.0		0.0003	0.2	bal.

The Tungsten Inert Gaswelding process was conducted to join similar AA6061-T6 plates with the process specifications demonstrated in Table 2. The aluminum AA6061-T6 plates with 200 x 300x 4 mm dimensions with V-joint groove type are prepared by cutting tools with coolant media to prevent excessive surface heating. In this current study, TIG welding with lower penetration with a V-groove was used in the 4 mm plate thickness to achieve full penetration and formation of the root face, and hopefully the welded joint has good strength. Furthermore, solution treatment of the welded AA6061-T6 at 520 °C for a holding time of 1.0 h was conducted using a muffle furnace and rapid water cooling. This process is followed by artificial aging at different temperatures (155, 185, and 215 °C) for an 8.0 h holding time. Based on the literatures can be drawn that temperature aging plays an important role in the microstructure evolution, in which the correct temperature results in better mechanical properties. The aging temperature has been used within the range 150 to 250 °C, in which the higher temperature potentially causes over-aging and reduces the strength. Thus, in this current study try to investigate the proper temperature for welding AA6061-T6 with a 4 mm plate thickness.

The aged samples were characterized by different methods, particularly the mechanical properties, referring to the AWS standard (AWS Committee, 2000). The scheme of the welded material and the test specimen arrangement is shown in Figure 1.

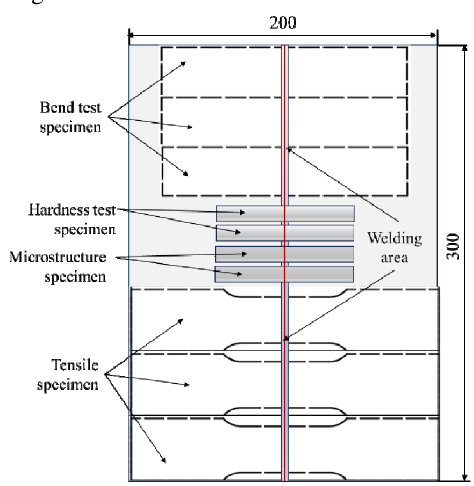

Figure 1. The schematic of the test coupon of aluminum AA6061-T6 was welded using TIG welding followed by artificial aging.

Table 2. TIG welding specifications and process parameters for a similar join of AA6061-T6.

Parameters	Value	Unit
Welding equipment	Migatronic pi/250	-
Tungsten electrode diameter	2.4	mm
Filler wire diameter	2.4	mm
Heat input	3.6	kJ/mm
Current	110	A
Voltage	14	V
Welding speed	4.19	mm/s
Welding grade	99	%
Shielding gas	Argon	-
Glass flow rate	15	L/min

Each of the specimens for hardness, tensile, and bending tests, as well as microstructural observation, was cut according to standard dimensions. Furthermore, microstructural observation was conducted using an optical microscope with 200× magnification. The metallography specimen was prepared through the grinding process, starting with a 100-2000 grit paper and followed by etching with a chemical solution of HF (hydrofluoric acid) for a 15-second etching duration. The Vickers hardness test with a load of 100 g was carried out to obtain the hardness of the weld metal (WM), heat-affected zone (HAZ), and base metal (BM) areas. The number of indentations in each area is three points for different artificial aging temperatures. Furthermore, the dimensions of the tensile and bending test specimens are shown in Figure 2. A total of three specimens for each of the experiments were tested at room temperature by using a Universal Testing Machine (UTM) with a load capacity of 30 tons. The mechanical testing was conducted with a typical crosshead speed of 5 mm/min at room temperature. The statistical analysis of the ultimate tensile strength data was carried out to calculate the standard deviation.

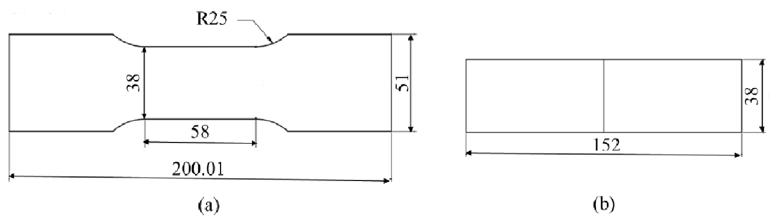

Figure 2. Dimensions of the mechanical testing specimens: (a) tensile strength and (b) bend test.

Furthermore, the experimental flowchart of this current study is demonstrated in Figure 3.

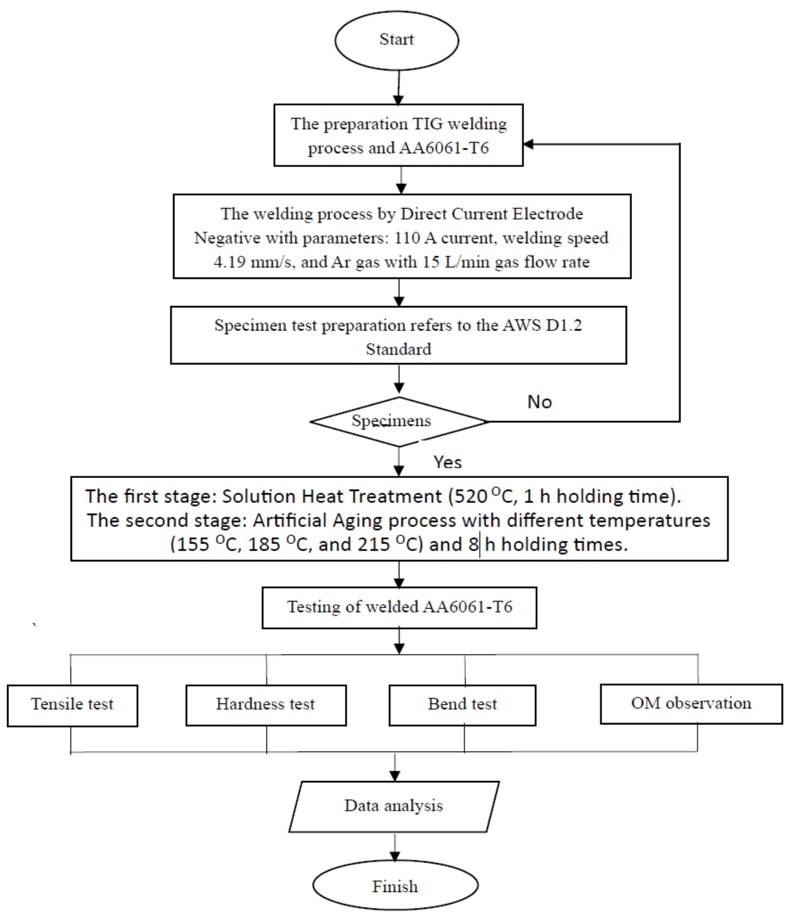

Figure 3. The experimental flowchart

3. RESULTS AND DISCUSSION

Figure 4 shows the A6061 plate welded using the TIG method followed by artificial aging. In this study, the plate samples were joined end-to-end with similar dimensions, forming a straight line on the surface of the 6061 plates, see Figure 4a. The detailed view of the welded plate, as shown in Figure 4b, clearly shows that the weld metal consists of weld metal (WM), heat-affected zone (HAZ), and base metal (BM), in which the BM area is not significantly influenced by heat input during the welding process. Based on macro-observation, these areas presented a different pattern, in which the weld metal area showed a circular pattern formed during the welding process. The circular pattern is suitable for aluminum sheets with a manual welding process, which has good heat and impurity control.

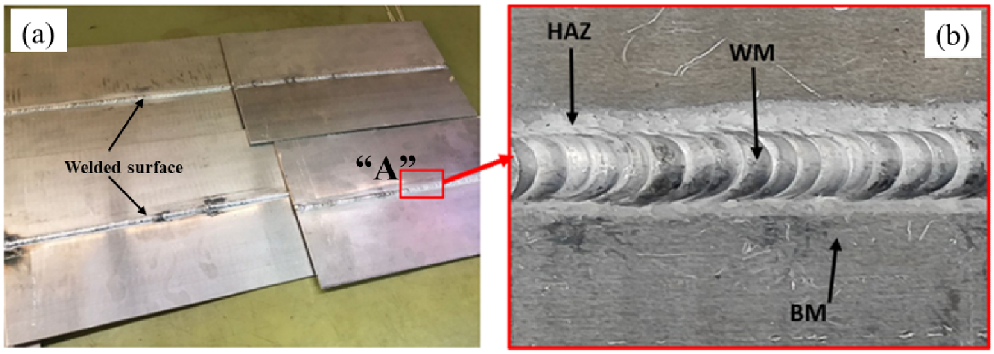

Figure 4. (a) Aluminum 6061 plate welded using the TIG method, and (b) Enlarged the "A" area.

Furthermore, the effect of aging temperature on the microstructural evolution of the A6061 welded plate was investigated by using an optical microscope (see Figure 5).

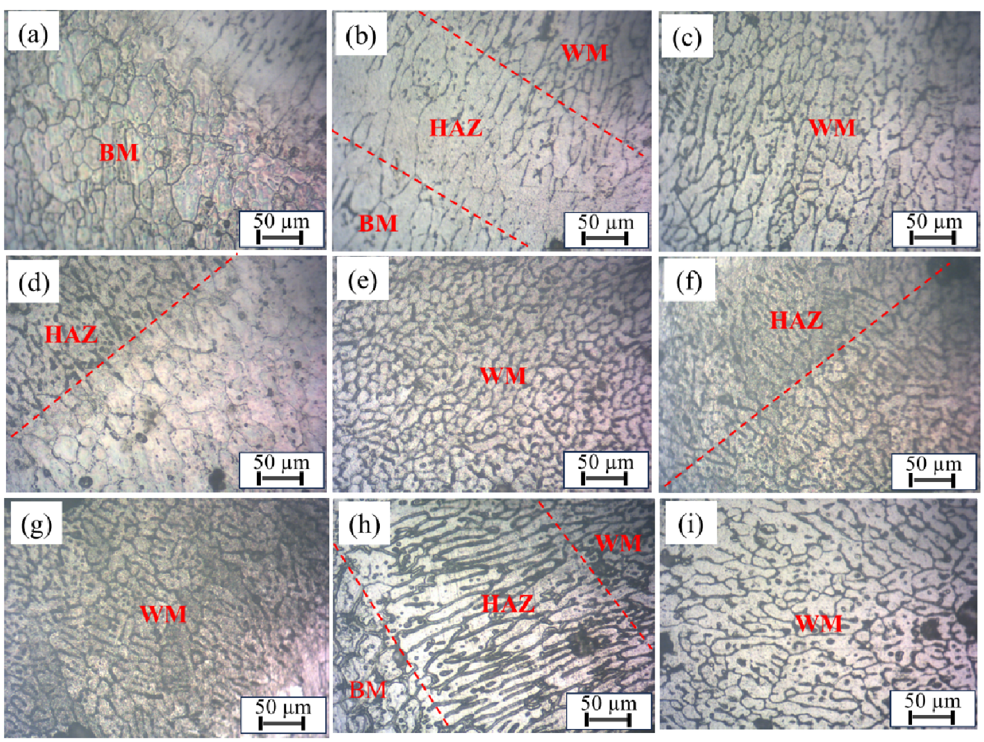

Figure 5. The microstructure of AA6061-T6 with different artificial aging temperatures: (a) Based metal, (b) HAZ-T155, (c) WM-T155, (d) HAZ-T185, (e) WM-T185, (f) HAZ-T215, (g) WM-T215, (h) HAZ-Non PWHT, and (i) WM-Non PWHT.

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The microstructure of the A6061 alloy mainly consists of α-aluminum solid solution with coarse grains smaller than 50 µm, see Figure 5a. The solid solution formed predominantly in the microstructure, which might be correlated with the low-alloy elements below 1 wt.% each (see Table 1). The low aging temperature (155 °C) promoted microstructural evolution of both HAZ and weld metal (WM) areas, see Figure 5b-c. Although the microstructure is not significantly different from that of the base AA6061-T6 alloy, a finer microstructure in the HAZ and WM areas was observed. The microstructure of the HAZ and WM area also demonstrated the continuously refined grain with the increase in aging temperature from 185 to 215 °C, see Figure 5d-g. The grain size below 10 µm was clearly observed in the WM area of the welded AA6061-T6 alloy. It is believed that the microstructure evolution strongly correlates with the strength. The solution treatment and aging process promoted Mg_2Si formation and microstructural evolution, further influencing the mechanical properties of the Al-Mg-Si alloy, as reported (Chen et al., 2023). The presence of fine precipitates within the microstructure of the AA6061-T6 can act as a barrier to dislocation movement. High temperature aging (215 °C) probably causes over-aging, which generates larger and more stable precipitates. Furthermore, the microstructure of the A6061 welded without the PWHT process showed little difference (Figure 5h-i). The grain structure with needle-like structure formation in the HAZ area was observed. The formation of this structure might be correlated with the impurities and rapid cooling rate of the HAZ area; this structure contributes to the low strength of the weld metal.

Figure 6 shows the hardness of AA6061-T6 alloy welded by using the TIG method, subsequent solution treatment, and artificial aging at different temperatures. A different hardness was observed in different areas: weld metal, HAZ, and base metal. This hardness strongly correlated with the different microstructure in each of the areas, as observed in Figure 5a-i. The as-welded material (T0) shows the lowest hardness in all of the different areas, with the highest hardness of 65.5 $HV_{0.1}$ and the lowest 58.1 $HV_{0.1}$ in the weld metal and HAZ areas, respectively. Furthermore, the increase in the hardness of welded AA6061-T6 was obtained for all of the areas after artificial ageing. A significant increase in the hardness occurred at an artificial aging temperature of 155 °C, the average hardness was 93.3 $HV_{0.1}$, 115.7 $HV_{0.1}$, and 123.1 $HV_{0.1}$ for WM, HAZ, and BM areas, respectively.

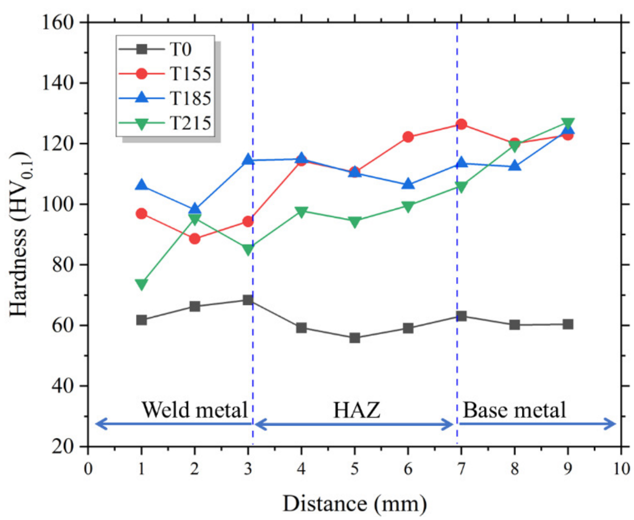

Figure 6. The hardness of AA6061-T6 welding with different artificial aging temperatures in different areas (WM, HAZ, and BM).

The maximum increase in hardness of the post-heat treatment sample (T155) up to 43% (WM), 100% (HAZ), and 101% (BM) compared with the as-welded AA6061 without heat treatment. This result corresponds to the microstructure, in which the artificial aging promoted microstructural evolution with a smaller grain size, see Figure 5a-c. On the other hand, the increase of aging temperature (T185-T215) also promotes microstructure change (see Figure 5d-g) and a slight increase of the hardness 106.3 $HV_{0.1}$ of the WM area obtained with 185 °C aging temperature. Furthermore, the decreased hardness of the WM and HAZ areas of the welded AA6061-T6 after 215 °C artificial aging occurred. This fact might be correlated with the higher aging temperature, which promoted larger precipitates dispersed within the microstructure. The hardness varies from 73 to 88 HV for the HAZ area without post-heat treatment of AA6061-T6 joined by TIG welding obtained (Ji et al., 2023). This value is higher than the hardness of the as-welded (T0), however lower than the hardness of aged AA6061-T6.

Without aging, the welding parameters like current, filler, and welding speed strong influences the hardness. Ji et al. use 240 A and 110 A welding current for this study. It is believed that the different of this parameter influence the hardness of welded AA6061-T6. Based on Figure 6, it is clearly visible that the most significant increase in hardness occurred at the base metal area. This fact is not easy to explain based on the microstructure or optical microstructure observation. However, it is believed that the composition of the AA6061 and precipitate formation during artificial aging contribute to enhancing the hardness. The formation of Mg_2Si in the AA6061 welding through artificial aging was also reported (Sugiarto et al., 2021).

Figures 7a-b show the tensile strength and strain of welded AA6061 aluminum with artificial aging and without the PWHT process (T0). It is clearly observed that the ultimate tensile strength (σ_{UTS}) of the welded AA6061 is influenced by the post-weld heat treatment. In this study, the highest strength of 201.4 MPa and strain of 5.5% were obtained for aged AA6061 at 185 °C. On the contrary, the aged material (T155 sample) had a strength of about 160.1 MPa, with the lowest strain 4.5% (see Figure 7b) being obtained. The lower aging temperature (T155) shows a lower strain of AA6061-T6 welding, which is slightly above that of the No-PWHT sample, which has 5.1%. Although the increase was not significant, the aging process clearly influences the mechanical properties of the AA6061-T6 welding. The increase in tensile strength might correlate with the microstructure evolution. In which the precipitate Mg_2Si and refinement contribute to the strength of the AA6061-T6 was reported (Moharami et al., 2020). Furthermore, the increase in the aging temperature up to 215 °C (T215 sample) tends to decrease the strength of the welded AA6061-T6, in which 160.3 MPa was obtained with 5.7% of strain. Ji et al. (2023) propose the tensile stress of welded AA6061-T6 to be about 115 MPa, this result is lower than 149.1 MPa without aging in the current study. The tensile strength tends to increase up to 201.4 MPa for 185 °C aging temperature. This fact confirmed that the post-weld heat treatment promoted the microstructure evolution and strength improvement. The main factor to decreasing of the strength of welded material is not easy to analyze. However, higher temperatures probably promoted more atomic diffusion and precipitate transformation. This phenomenon can generate coarse precipitates within the microstructure, and it is detrimental to tensile strength.

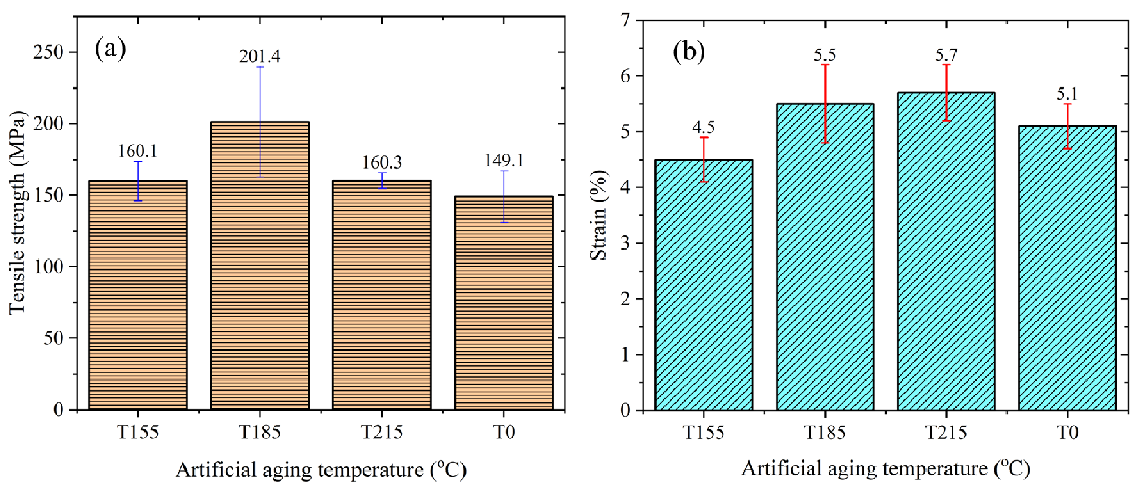

Figure 7. (a) Tensile strength and (b) strain of the welded AA6061-T6 with different aging temperatures.

In the fracture of the welded AA6061-T6 samples presented in Figure 8, it is clearly visible that the fracture area for all of the samples occurred at the weld metal (WM) areas. In this study, the introduction of the artificial aging process did not significantly change the properties of the WM area in comparison with the base metal. This finding confirms that the WM zone has the lowest strength. This result corresponds to the hardness result, which has the lowest hardness. In the ultimate tensile test, attention should be paid to check the plate sample dimensions accurately to obtain a consistent result.

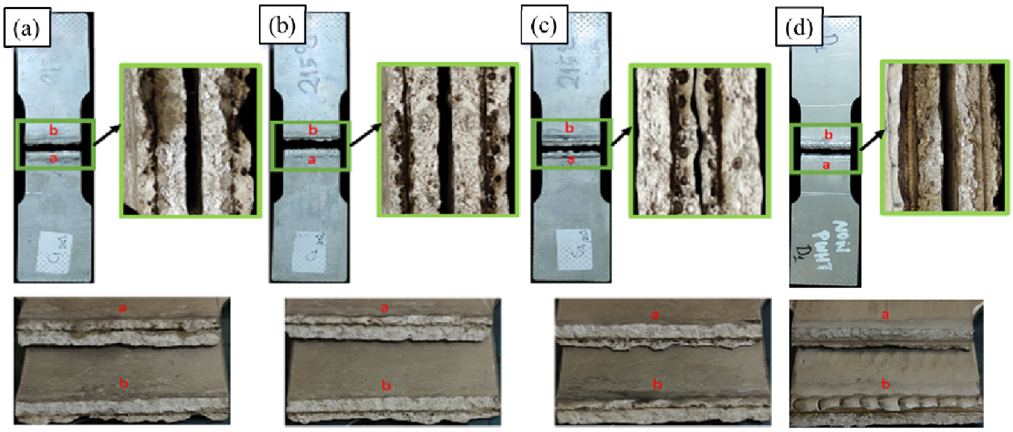

Figure 8. The fracture area of the welded AA6061-T6 with different artificial aging temperatures: (a) T155, (b) T185, (c) T215, (d) WM-Non PWHT/T0.

The bending test samples were observed at the face and root and are presented in Table 2. It is clearly observed that the face area of the specimens with different artificial aging temperatures is “accepted” because no cracks occur, or the crack length is below 6 mm. On the other hand, the root areas show a different condition. The test samples T155 and No-PWHT are “accepted” conditions, which might be correlated with their ductility. On the other hand, the test samples T185 and T215 demonstrated more crack formation on the surface of the root area after bending. The formation of cracks is influenced by many factors, such as weld defects. It is believed that the welding defects, such as pores contribute to initial crack formation. The relation between the pores and crack formation of the Al-Mg-Si alloys was also reported (Lee et al., 2024).

Table 2. Bend test of the coupon with different aging temperatures

Specimen	Crack	
	face	root
T155	Accepted	Accepted
T185	Accepted	Not Accepted
T215	Accepted	Not Accepted
No-PWHT	Accepted	Accepted

In this study, the morphologies of test samples at the root area are shown in Figure 9. Based on the observation, the root area clearly exhibits an open crack model, likely due to tensile phenomena at the outside radius of the T185 and T215 weld tests.

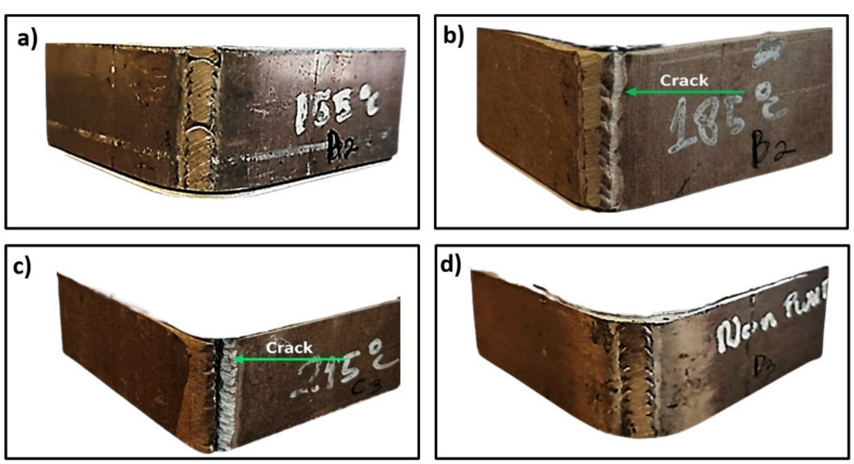

Figure 9. The root surface of the bend test of the AA6061-T6 with different artificial aging temperatures: (a) T155, (b) T185, (c) T215, (d) WM-Non PWHT/T0.

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The introduction of PWHT into welded similar joints of the AA6061-T6 with artificial aging temperatures (155, 185, and 215 °C) was successful. The finding shows that the aging temperature can be used to improve the hardness in the HAZ area and achieve a higher tensile strength than that of as-welded aluminum. Even though the bend test shows the crack occurred on the root side, the PWHT at 185 °C mostly brings a good effect on the tensile strength of the welded AA6061-T6.

4. CONCLUSION

The joining of the Aluminum 6061 by TIG welding and characterizing its properties was carried out. Based on the data above, several conclusions can be drawn. Larger grains were observed in the base metal microstructure. In which the subsequent artificial aging of TIG welding promoted microstructure evolution, and finer grains formed in the HAZ and WM areas. Artificial aging significantly increases the hardness of the weld metal across all areas. Even though the highest hardness at the base metal was obtained at the highest artificial aging temperature, the predominant increase in hardness was achieved by the introduction of a lower aging temperature. Furthermore, aging at medium temperature successfully enhances tensile strength and strain over those of as-welded aluminum and high-temperature aging. The fracture morphologies demonstrated that the fracture area occurred in the WM area. This result confirmed that this area has weaker strength than the other area. On the other hand, the bending test shows a crack formation in several samples. In the root area, this phenomenon was observed as more visible. The introduction of different aging temperatures during the PWHT process in the welded AA6061-T6 influences the microstructure evolution and also improves the mechanical properties of the welded aluminum alloy. It is clearly obtained that the aging temperature does not linearly increase the strength of the welded AA6061-T6 material, particularly for aging at 180 °C shows the highest strength in this current study. In comparison with previous studies, this result is still within the range of strength of the welded AA6061-T6. This research contributed to engineering applications to avoid over aged phenomenom, which cause reducing in the mechanical properties of welded aluminum. The introduction of the correct temperature will maximize the properties of welded AA6061-T6. In the future, a deeper investigation correlated with the precipitate formation is still important, including the XRD test and SEM-EDS observation, which might be helpful to increase the comprehensive analysis in the welded AA6061-T6.

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