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Technical Report

Effect of a post-weld heat treatment on the mechanical and microstructure properties of AA6061 joints welded by the gas metal arc welding cold metal transfer method

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ABSTRACT

This work studies the effect of a post-weld heat treatment (PWHT) on the mechanical and microstructure properties of an AA6061 sample welded using the gas metal arc welding (GMAW) cold metal transfer (CMT) method. The CMT method was used because the method provides spatter-free welding, outstanding gap bridging properties, low heat input and a high degree of process flexibility. The welded samples were divided into as-welded and PWHT samples. The PWHTs used on the samples were solution heat treatment, water quenching and artificial aging. Both welded samples were cut according to the ASTM E8M-04 standard to obtain the tensile strength and the elongation of the joints. The failure pattern of the tensile tested specimens was analysed using scanning electron microscopy (SEM). A Vickers microhardness testing machine was used to measure the hardness across the joints. From the results, the PWHTs were able to enhance the mechanical properties and microstructure characteristics of the AA6061 joints welded by the GMAW CMT method.

1. Introduction

Alloys have become some of the most widely used materials in such industries as the structural and transportation industries because of their good mechanical properties, including corrosion resistance, light weight, high strength, high toughness and recycling capabilities [1]. Alloy 6061 is one of the most widely used alloys in the 6000 series. This standard structure alloy, one of the most versatile of the heat-treatable alloys, is popular for medium- to high-strength requirements and has good toughness characteristics. Applications for the alloy range from transportation components to machinery equipment applications to recreational products and consumer durables. Aluminium alloy 6061 has been used in the automotive industry [2], in marine frames and in pipeline and aircraft applications [3]. This type of aluminium alloy contains magnesium and silicon as its major alloying elements [4]; they increase the strength of the alloy via precipitation hardening [5].

A recent development in welding technology is the cold metal transfer (CMT) process, which is ideally suited to welding aluminium because of the no-spatter welding process and the low thermal input. CMT is a modified metal inert gas (MIG) welding process. The principal innovation is that the motions of the wire have been integrated into the welding process and into the overall control of the process. Every time a short circuit occurs, it interrupts the power supply and controls the retraction of the wire. The wire retraction motion assists droplet detachment during the short circuit; thus, the metal can transfer into the welding pool without the aid of the electromagnetic force. As a result, the heat input and spatter can be decreased significantly [6].

Usually, the microstructure and the mechanical properties of an aluminium alloy will change after the welding because of the melting of the base material during the welding process. This contributes to its lack of strength. To overcome this problem, a heat treatment is performed to the welded part to obtain the desired mechanical properties and to relieve the residual stress on the part [3]. The properties of various aluminium alloys can be altered by specifically designed heat treatments. Heat treatments for aluminium alloys are usually performed by solution heat treatments, followed by water quenching and aging at a certain temperature or by natural aging in air [2].

Many researchers are now focused on finding a material that can replace metal. Metals are excellent building materials because of their high strength, high toughness, high melting temperature and high chemical reactivity; because of this, metal is preferred for construction applications [7]. A good example of a metal is steel. Steel can be defined as an iron–carbon alloy containing 0.02–2.11% carbon. It is the most important category within the ferrous metal group. Applications of steel include construction (bridges, I-beams), transportation (trucks, rails) and consumer

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products (automobiles and appliances). However, steel has some disadvantages, such as a low corrosion resistance, a typically heavy weight and a high expansion rate in changing temperatures. It also has high initial processing costs. Through research conducted several years ago, a new material has been found that can replace steel in some applications. This new material is an aluminium alloy with light weight, corrosion resistance and attractive mechanical properties. The construction and transportation industries currently use this material instead of other metals [1].

For aluminium alloy, the most common joining method is welding. In the United Kingdom and Europe, gas metal arc welding (GMAW) is the main process employed for joining pieces of aluminium alloy in the construction of rail vehicles, ships, steel bridges and pressure vessels [8]. The advantages of using welding as a joining process include its high joint efficiency, the simple set up, its flexibility and the low fabrication costs. Although it has many positive properties, welding involves melting the base material; thus, the microstructure and the mechanical properties of the material will be different than before the material was welded [7]. To obtain the desired properties for the welded material, a heat treatment can be implemented [9].

Heat treatment involves various heating and cooling procedures performed to cause microstructure changes in a material, which in turn affect its mechanical properties. In other cases, heat treatment is used to relieve the effects of strain hardening that occur during forming so that the material can be subjected to further deformation [7]. The thermal treatment for aluminium alloy 6xxx series consists of three main processes [10]: solution heat treatment, quenching and ageing.

There are a few publications that have used the GMAW CMT method. For example, the arc characteristics and metal transfer behaviour of CMT method and its use in joining aluminium to zinc-coated steel has been investigated [11], and it was found that the metal transfer process is very stable. The arc heating behaviour changes based on the special wave control features. Joining dissimilar metals—joining aluminium to zinc-coated steel—without cracking with the CMT process in a lap joint is possible. Research on the characterisation of the CMT process and its application for low-dilution cladding has shown that the technology can be used as a cladding process because of the precise control of the weld bead dilution and the fact that a lower dilution ratio is possible than that realised with pulsed MIG welding [12].

A number of research works have investigated the application of post-weld heat treatment (PWHT) to welding joints using several welding processes. For instance, study [13], on the effect of pre/post T6 heat treatment on the mechanical properties of laser-welded semi-solid metal cast A356 aluminium alloy, showed that a post-T6 heat treatment increases the tensile strength and hardness, compared with as-welded and pre-T6 heat treatment joints. For the friction stir-welding process, a suitable PWHT enhanced the tensile properties of the friction stir-welded AA6061 aluminium alloy joints [14]. Recent works [15] have shown that the microstructure and the mechanical properties of friction stir-welded Al–Zn–Mg alloy in heat-treated conditions lower the mechanical properties, such as yield strength and ultimate tensile strength, but improve the percentage of elongation. Investigations on post-weld heat-treated 7449 aluminium alloy thick plates highlighted that the application of PWHT to a friction stir weld has a dramatic effect on the nugget and thermo-mechanically affected zone (TMAZ) microstructures and hence on the hardness within the weld zone [16].

The effects of a pulsed current and a post-weld aging treatment on the tensile properties of argon arc-welded high-strength AA7075 aluminium alloy were studied in [17], and it was discovered that the joints fabricated by pulsed-current gas tungsten arc welding exhibit very high strength. The enhancement in strength is approximately 25%, compared with continuous-current gas metal arc welding joints, and an additional enhancement in strength of 8–10% is obtained because of the simple post-weld aging treatment, irrespective of the welding techniques used. A study on 7075 T6 aluminium alloy [18] showed that the strengthening behaviour in PWHT tungsten inert gas (TIG) weld/heat-affected zone (HAZ) is clearly associated with a balance of dissolution, reversion and precipitation processes across the HAZ, and the post-weld aging treatment applied to the joints was found to increase the tensile strength of welded joints. The enhancement of the stress corrosion crack (SCC) resistance of AA7005 welds with appropriate filler metal and PWHT was investigated [19], and this study found that the SCC resistance of AA7005 welds can be enhanced through proper selection of the filler metal and through a PWHT. The combination of ER5356 filler metal and post-weld T7 treatment can provide the AA7005 weld with good SCC resistance and high tensile strength. It was also discovered that the superior mechanical properties (higher yield strength and hardness), preferred microstructures in the weld metal region (very fine equi-axed grains with higher amount of precipitates) and favourable residual stress field in the weld metal region (large magnitude of compressive stress) are the reasons for the better fatigue performance of the post-weld aged pulsed-current gas tungsten arc welding joints of AA7075 aluminium alloy [20].

The effect of heat treatment on the microstructure and the corrosion behaviour of Al6061 alloy using gas tungsten arc welding (GTAW) has been investigated [21]. It was discovered that the heat treatment process changes the morphology of the course particles from an irregular shape to an almost globular shape. In another study [22], the mechanical behaviour of the 6061-T6 aluminium alloy at room temperature for various previous thermal histories representative of electron beam welding was investigated, and it was discovered that the yield stress decreases if the peak temperature increases and the heating rate decreases. These variations were explained by coarsening of the precipitates.

From the literature review, it is understood that very little research has been published to date on welding using the GMAW CMT method and that there is no reported research on the effect of a PWHT on AA6061 joints welded by the GMAW CMT method. Hence, the present investigation has been performed to understand the influence of PWHT (solution heat treatment, quenching and artificial aging [160 °C–20 h]) on the microstructure and the mechanical properties of aluminium alloy AA6061 joints welded by the GMAW CMT method.

2. Research methodology

The material used in this experiment was 6061 aluminium alloy with a thickness of 10 mm. The material was cut into several pieces with widths of 100 mm according to the standard length of ASTM E8M 04 [23]. The cutting process was conducted using an automatic cutting machine. Grooving was done using a milling machine with an angle of 40° for each cutting part, according to the specification of a single V–groove joint, as shown in Figs. 1 and 2.

The GMAW CMT method was used to weld the material. This machine is equipped with a peak current controller, which is responsible for establishing the arc length, and it provides sufficient energy to preheat the work piece to ensure a good fusion. The type of filler used for the welding process was ER 4043 with a diameter of 1.2 mm. The chemical composition of the filler is shown in Table 1, and the welding parameters used during the process are shown in Table 2. The welding samples were divided into two groups: as-welded and PWHT samples.

The work piece material was wiped with ethanol before the welding process to remove impurities, such as oil and grease, that are typically present after the cutting and grooving process.

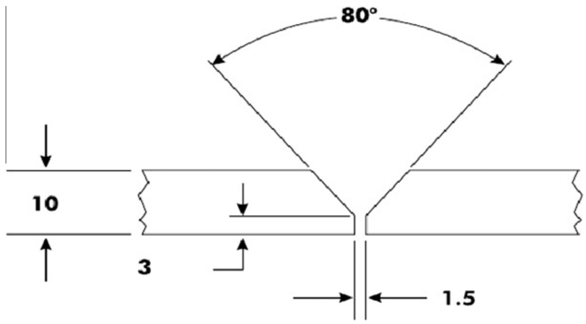

Fig. 1. Single V–groove joint (mm).

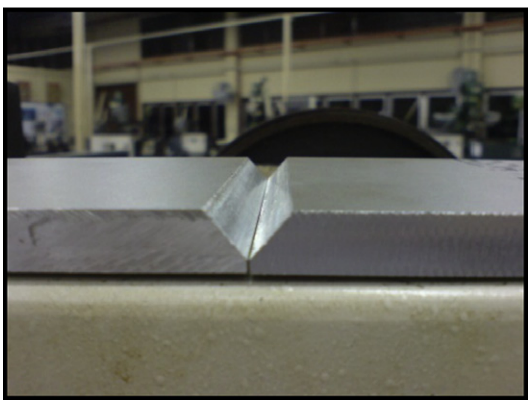

Fig. 2. Complete grooving.

Table 1
Chemical composition of filler.

Material	Al	Si	Mg	Cu	Fe	Mn	Zn	Ti
ER 4043	92.9	5.6	0.05	0.3	0.8	0.05	0.1	0.02

Table 2
Welding parameter.

Joint	Current (A)	Voltage (V)	Feeding speed ($mm\ s^{-1}$)	Heat input ($mm\ s^{-1}$)	Travel speed ($mm\ s^{-1}$)	Air flow ($L\ min^{-1}$)
Single V	210	24	190	1.4	3.6	23.6

The PWHTs used were solution heat treatment, water quenching and artificial aging. The samples were solutionised in the induction furnace at 530 °C for 1 h. The samples were then cooled down rapidly by immersion in a water bath. The samples were age hardened at a temperature of 160 °C for 20 h.

Specimens for the tensile test were made according to the ASTM E8M 04 standard [23]. A CNC milling machine was used to cut the welded samples into the specific dimensions, as shown in Figs. 3 and 4. The tensile test was performed at 100 kN and a speed of 1 mm/min using a Universal Testing Machine. Scanning electron microscopy (SEM) uses a focused beam of high-energy electrons to generate a variety of signals at the surface of solid specimens. The signals that are derived from electron-sample interactions reveal information about the sample, including external morphology (texture), chemical composition, crystalline structure and orientation of materials making up the sample. The micrograph produced shows surface topography and chemical contrast for the shortest time. In this work, JEOL JSM-5600LV SEM equipment was used. Before performing SEM, the specimen was dipped into liquid nitrogen to promote and ease brittle fractures in the sample.

3. Results and discussion

3.1. Tensile strength and hardness

Tensile strength was calculated based on the average of four stress values, as presented in Fig. 5. The tensile strength values for the PWHT and as-welded samples were 55.32–53.31 MPa, respectively. Thus, a 3.8% increment was achieved when implementing PWHT on the welded joints. An increase in tensile strength of PWHT 6063 aluminium alloy welded by the GMAW method was also observed in [24], where solution and ageing heat treatments were applied, producing an increase in tensile strength due to the strongly modified microstructure.

A Vickers microhardness test was done at three different locations: at the top, middle and bottom sections of the surface weld region, with a load of 0.2 kg. The average hardness values are shown in Table 3. Fig. 7 shows the hardness value for each position of both the as-welded and PWHT samples, and Fig. 8 shows the average hardness values for the as-welded and PWHT samples. As presented in Table 3 and Fig. 7, the bottom region of the as-welded sample had the highest hardness value—76.9 HV. However, the top and middle regions of the PWHT sample had the highest hardness value—87.5 HV. For the average hardness value, the highest value recorded for the PWHT sample was 86.41 HV. For the as-welded sample, the hardness value was 68.8 HV. By implementing PWHT for welded AA6061, the hardness value was significantly increased by 25.6% compared with the as-welded sample.

The percentage of elongation was taken at average value, as shown in Fig. 6. The percentage of elongation for PWHT and as-welded samples were 8.13% and 6.69%, respectively. Thus, PWHT applied to the samples increased the percentage of elongation by 21.5%. This is because, for an aluminium alloy, it is known that the ductility of the material is obtained from the solution heat treatment (SHT) stage [10]. This increase in ductility is mainly due to a reduction in the barriers to flow that affect the steady-state flow stress. This is because the material is held at an elevated temperature for enough time that all of the constituents are taken into the solid solution, producing one single phase.

Higher values of hardness, tensile strength and elongation highlight the superiority of PWHT applied to CMT–welded joints compared with the as-welded joints of AA6061. This could be explained by the fine and uniform distribution of precipitates at the weld joints that are obtained by applying PWHT, along with good characteristics of the GMAW CMT method, such as spatter-free welding, outstanding gap bridging properties and low heat input. The performance of the GMAW CMT method for joint welding was investigated in [12], where it was discovered that the CMT welds exhibit a diminishing dilution ratio with a potentially less crack-susceptible composition range of Al 2024 with filler wire 4043. Thus, the combined effect of a higher tensile strength and a higher ductility of the PWHT joint offers enhanced resistance to crack initiation and crack propagation and hence improved mechanical properties for the PWHT joint. Higher hardness, tensile strength and elongation values for PWHT-welded joints, compared with as-welded joints only, solution-treated joints only and artificially aged joints only for electron beam welding of AA2219 aluminium alloy was also reported in [25]. It was found that the weld metal region of a PWHT joint consists of a very fine and uniform distribution of precipitates compared with other joints, and this was determined to be the main contributor to the superior

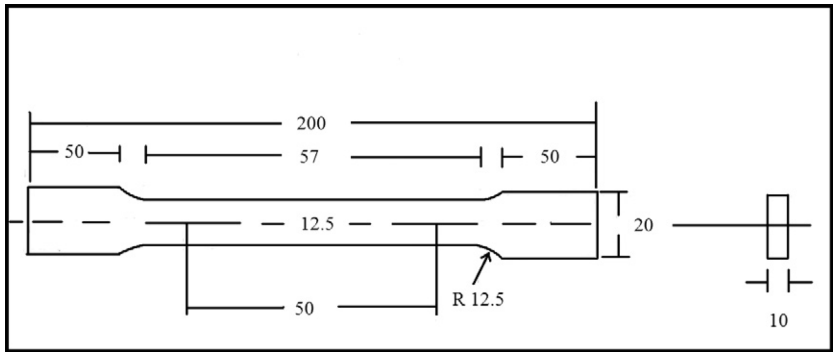

Fig. 3. Tensile test dimension (mm).

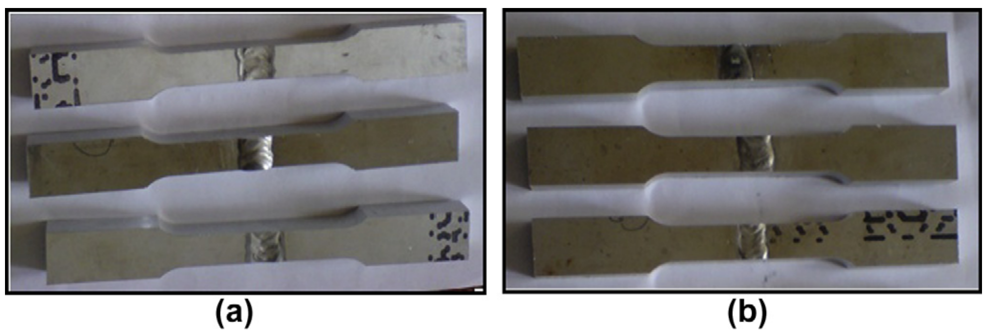

Fig. 4. (a) As-welded tensile specimens; (b) treated tensile specimens.

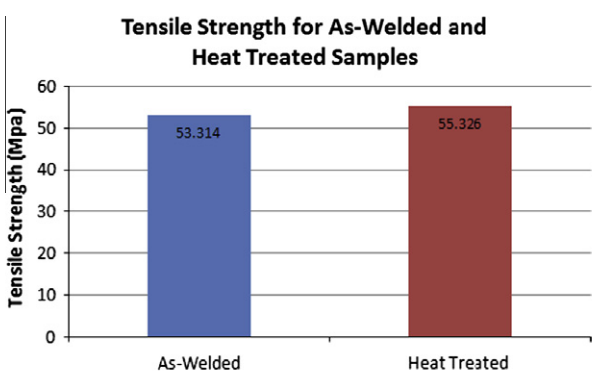

Fig. 5. Bar chart of tensile strength of as-welded and heat treated samples.

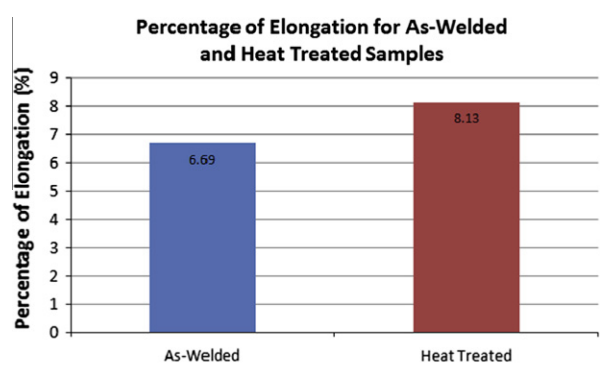

Fig. 6. Bar chart of percentage of elongation of as-welded and heat treated samples.

Table 3
Hardness value (HV) for as-welded and heat treated samples.

Sample	Top (HV)	Middle (HV)	Bottom (HV)	Average (HV)
As-welded	67.2	62.3	76.9	68.8
Heat treated	87.5	87.5	84.2	86.41

tensile and hardness properties of PWHT joints. This is also evident from other investigations [13,26], which found that fine dimples increase the tensile strength and hardness. This was attributed to precipitation hardening in the weld metal region.

The strength of the PWHT AA6061 welded joint was achieved with an ageing process. The increase in strength of PWHT AA6061 welded joints is due to a diffusion-assisted mechanism that causes an increase in the density of the GP zones, distortion of the lattice planes and hindering of dislocation movement by the impurity atoms. The GP zones are coherent with the aluminium matrix, with internal ordering of Al/Mg on the matrix lattice. The strengthening effect can also be the result of interference with the motion of the dislocation because of the formation of precipitates. For instance, a high diffusion coefficient for Mg in an aluminium matrix was observed for PWHT of an AA6061 aluminium alloy welded joint [27]. From [14], it was discovered that, in an artificially aged joint (AG), the precipitates are very fine and seem to be uniformly distributed throughout the matrix. This leads to an increase in dislocation density, which results in an improvement in hardness and enhanced tensile properties. From the EDAX results, this study identified $MgSi_2$ as the predominant precipitate in all of the joint variations.

All tensile samples broke in the HAZ, which suggests that the HAZ still has a lower plastic deformation capability than the rest of the base alloy. However, because the weld has a higher strength

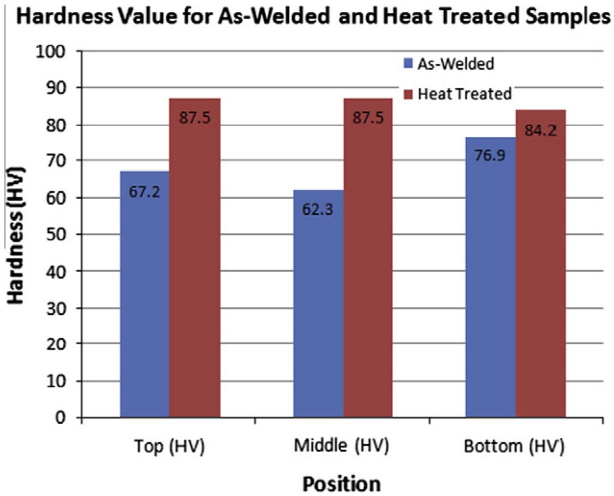

Fig. 7. Hardness value for each position of both as-welded and heat treated samples.

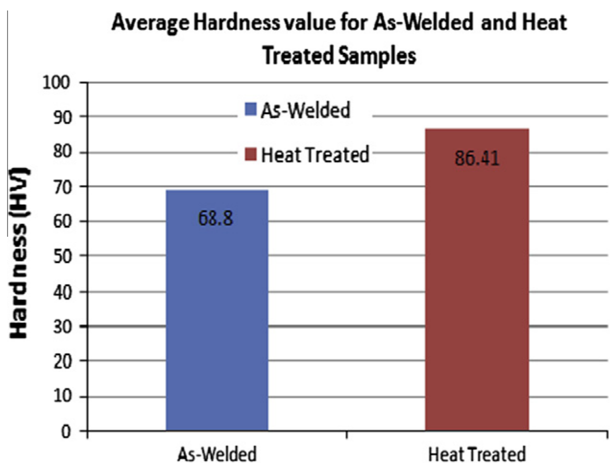

Fig. 8. Average hardness value for both samples.

level because of the PWHT application, the elongation or deformation is no longer concentrated in the HAZ. A welded structure therefore has a relatively good deformation capability. Therefore, the limited elongation capability of the tensile specimen for an as-welded joint was due to the fact that the total elongation of the specimen during testing was concentrated in the HAZ, which is the weakest part of the specimen.

3.2. Fracture surfaces

The fracture surfaces of the tensile specimens were characterised using SEM to understand the failure patterns of the welded AA6061. SEM micrographs were taken at three different locations: the top surfaces, the centre regions and the bottom (root) portions of the joints. All of the fractographs are presented in Figs. 9–11.

Fig. 9 shows the size and spacing between grains produced at the top surfaces of the welded region. The spacing between the grains was indicative of the ductility of the welded joint. In the as-welded joint, the grains were large, and the distance between grains was high compared with the heat-treated specimens, in which the grain size was constant and fairly small and the grains were located close to each other, as shown in Fig. 9b. As is clear from the mechanical tests, the strength of the alloy after PWHT was generally improved, but the region of the HAZ was still the weakest area, and the material generally failed at that point.

The fractographs taken in the middle portion of the tensile fracture surfaces is shown in Fig. 10. The dimples on the fracture surfaces of the as-welded specimen were larger than those on the heat-treated specimens, in which the dimples were very fine. It can be observed that the dimples dominated the fracture surfaces, reflecting the fact that most of the failure was the result of ductile fracture. This conclusion is also supported by Hu and Richardson [26], which reported that the solution heat-treated samples contained a large number of fine dimples. The fine dimples indicate a ductile-type failure. For ductile material undergoing tensile testing, voids generally form prior to necking. However, if a neck is formed earlier, the void formation becomes much more prominent, as the coarse and elongated dimples shown in Fig. 10a illustrate. This is also evident from [17], which found coarse and elongated dimples in PWHT pulsed-current GMAW joints.

Usually, metal consolation was poor in the root region of the welded area because of the low welding quality; the weldment did not penetrate the base metal well, and this could be the reason for the brittle-like failure in the root region. As shown in Fig. 11, cleavage failure patterns were revealed. Smaller cleavage facets were seen in the heat-treated joints than in the as-welded joints, where larger cleavage facets were observed. This is also evident from [14], in which relatively large cleavage facets were seen in as-welded joints, compared with artificially aged joints, for which smaller cleavage facets were observed. By implementing PWHT for a welded AA6061 sample, a high load was needed to break the specimen, at the same time contributing to smaller cleavage facets.

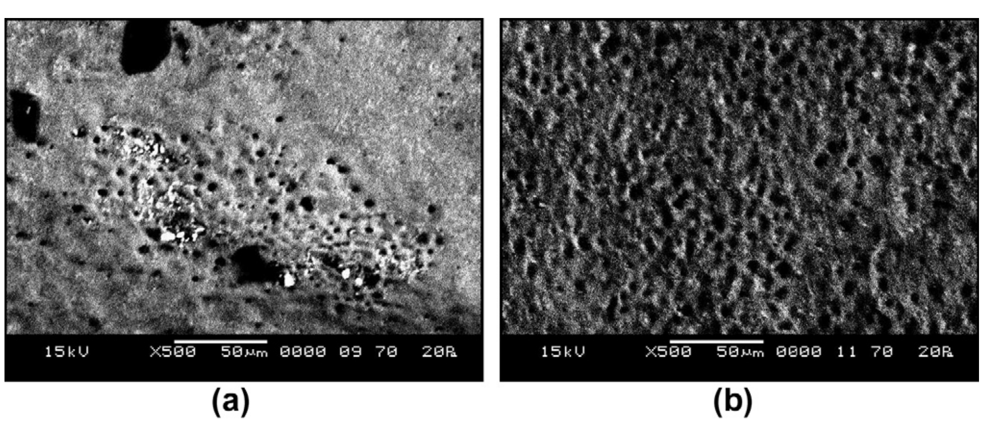

Fig. 9. SEM fractographs of the top surfaces of tensile tested specimens; (a) as-welded; (b) heat treated.

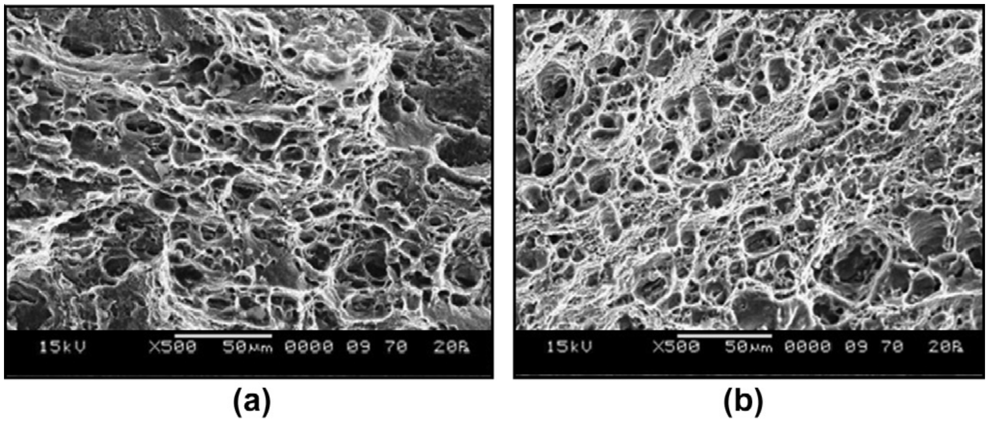

Fig. 10. SEM fractographs of the weld centres of tensile tested specimens; (a) as-welded; (b) heat treated.

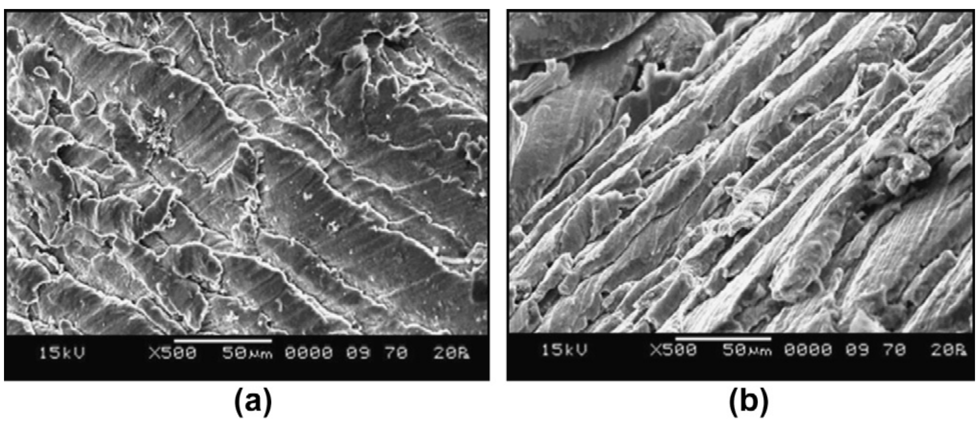

Fig. 11. SEM fractographs of the root regions of tensile tested specimens; (a) as-welded; (b) heat treated.

4. Conclusions

In this paper, the effect of PWHT on the mechanical and microstructure properties of welded AA6061 using the CMT GMAW method has been analysed. From this investigation, the following important conclusions have been derived:

- By implementing PWHT, a 3.8% increase was recorded for tensile strength, hardness strength was increased by 25.6% and a 21.5% higher elongation was achieved. The results proved that PWHT was able to enhance the hardness strength and tensile properties of AA6061 welded joints using the GMAW CMT method.
- The higher values of hardness, tensile strength and elongation are due to the fact that PWHT produces a fine and uniform distribution of precipitates at the weld joints. The good characteristics of the GMAW CMT method, which produce weld joints with spatter-free welding, outstanding gap bridging properties and a low heat input, were also involved.
- From SEM fractographs, a smaller grain size, a smaller gap between the grains and relatively small voids were observed for the PWHT joints. These qualities led to the superior tensile properties, compared with the as-welded joint.
- The welded structure has a relatively good deformation capability because the weld had a higher strength level as a result of the PWHT application. Thus, the elongation or deformation is no longer concentrated in the HAZ. Therefore, the limited elongation capability of the tensile specimen for an as-welded joint is due to the fact that the total elongation of the specimen during testing was concentrated in the HAZ, which is the weakest part of the specimen.

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