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ORIGINAL ARTICLE

Effect of Pre and Post Weld Heat Treatment on the Mechanical Properties of Friction Stir Welded AA6061-T6 Joint

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ABSTRACT – This research work focuses on the study of the improvement of mechanical properties, specifically the tensile strength of 6061-T6 aluminum alloy on prismatic specimens with 9.5 mm thickness that has been subjected to friction stir welding process and two heat treatments; solubilized and aging before or after the welding process. Three cases studied and evaluated were, welding of the base material without heat treatment (BMW), solubilized heat treatment and partial aging of the base material before welding (HTBW), and heat treatment of solubilized and aging of the base material after welding (HTAW). The obtained results show an increase of about 10% (20 MPa) of tensile strength for the HTBW process, compared to BMW case. In addition, for the case of HTAW, the obtained tensile resistance presents a joint efficiency of 96%, which is close to the tensile strength of the base material (≈310 MPa).

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Friction stir welding;
Solubilised heat treatment;
Ageing heat treatment;
Tensile strength.

INTRODUCTION

The friction stir welding process was discovered and patented by the Welding Institute in 1991, [1]. This welding process in solid-state consists of a non-consumable tool formed by a shoulder and a pin, where the union is carried out by frictional heating and plastic deformation generated by the tool in the materials to be joined [2-4]. In the beginning, this process of welding on thin aluminium alloys was limited, but nowadays, the application of this welding technique in different materials and different thicknesses has been highly developed [5-7]. The aluminium alloy 6061-T6 is widely used in the industries: aerospace, marine, automotive, because it offers a very good balance between weight, mechanical properties and resistance to corrosion [8-11].

Friction stir welding is a solid-state process, which is differentiated from the traditional fusion welding processes such as MIG, TIG and coated electrode. It presents an improvement in mechanical properties of the welded materials; a significant saving of energy during the union and a decrease of contaminants [12-15]. Furthermore, the joint of 6061-T6 aluminium alloy made by traditional technique, such as fusion, presents two types of problems. The first one is the appearance of characteristic defects of the type of welding used and the second problem is the thermal cycle that occurs during welding; both problems affect the original mechanical properties of the material [12]. The use of suitable parameters, materials and protection elements during welding have provided a decrease or disappearance of the defects present in the joint; thus, reducing this problem and enhancing the mechanical properties of the welded materials [13, 14]. The thermal cycle that is inevitably generated during welding is the main cause of the loss of up to 43% or more of its main mechanical properties, limiting its uses only to certain industrial applications. [15]. This problem has been intended to solve by means of thermal treatments after welding [16]; nevertheless, this solution brings with it a series of limitations and problems, among which it can highlight the following: the high consumption of energy applied during thermal treatments and the restriction of dimensions of the pieces that subjected to heat treatment [17, 18]. Therefore, this research focuses on the improvement of the tensile properties of the friction stir welded 6061-T6 aluminium alloy, by means of thermal treatments [19, 20], which in this work are: solubilized and ageing (partial and total). Another objective is to reduce the heat treatment times after welding, which provide the material with tensile mechanical properties close to the base material.

EXPERIMENTAL DETAILS

Materials and Welding Parameters.

The material used in this investigation was alloy 6061-T6, with chemical composition given in Table 1 and the principal mechanical properties shown in Table 2. The prismatic specimen used for friction stir welding has the dimensions of 150 mm (length) × 100 mm (width) × 9.5 mm (thickness), and the equipment used to perform this modality of welding was a three-axis machining centre with 15 hp of power and a maximum rotation speed of 6000 rpm. The tool is made of H13 steel, with dimensions shown in Figure 1. The parameters for the friction stir welding process in this

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investigation were kept constant at rotation speed of 1000 rpm, feed speed of 90 mm/min, penetration speed of 9 mm/min, and holding time of 10 seconds. The last parameters were selected to reduce the defects of welding [21].

Table 1. Chemical composition of aluminium alloy 6061-T6.

Element	Cr	Cu	Fe	Mg	Mn	Si	Ti	Zn	Other
Wt.%	0.375	0.275	0.6	1.0	0.15	0.7	0.14	0.24	0.15

Table 2. Principal mechanical properties of AA 6061-T6.

Density (kg/m^3)	UTS (MPa)	σ_y (MPa)	E (GPa)	Fatigue limit (MPa)	Poisson ratio	Brinell hardness
2700	310	275	69	95	0.33	95 (500 Kg/10 mm)

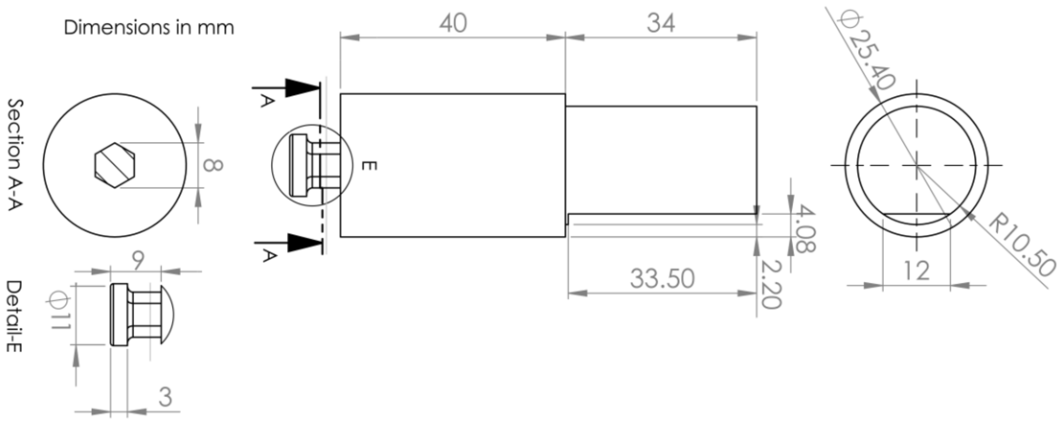
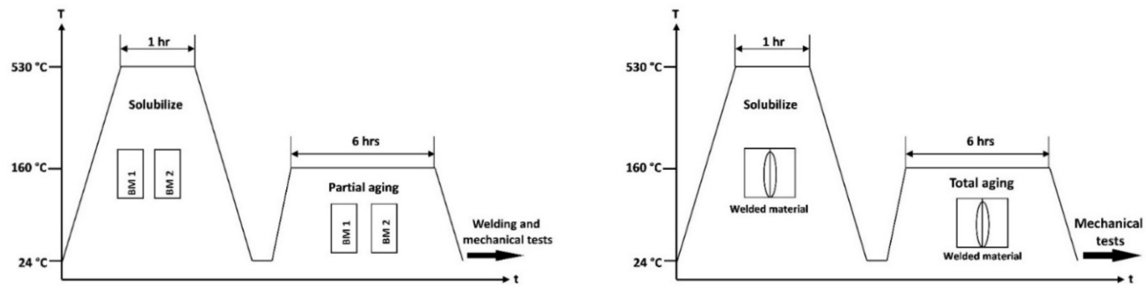


Figure 1. Dimension of friction stir welding tool.

Heat Treatment

The heat treatments were initiated by solubilizing, followed by partial ageing and total ageing. The first heat treatment was carried out at a temperature of 530 ° C, for 1 hour to dissolve the precipitates and homogenise the chemical composition of the material [22-24]. The heat treatment of partial ageing and total ageing were carried out at a temperature of 160 °C for 6 hours; both heat process before and after welding are illustrated in Figures 2(a) and 2(b), respectively [25].



(a) (b)

Figure 2. (a) Heat treatment before welding (HTBW), and (b) heat treatment after welding (HTAW).

The two heat treatments were cooled in the water at a temperature of 24 ° C. Three cases studied were:

i. welding on base material without any heat treatment (BMW),
ii. solubilized firstly and then partial ageing of the base material before welding (HTBW) and
iii. solubilized firstly and then total ageing of the base material after welding (HTAW).

For the heat treatment of solubilized in the case of HTAW, the material was already welded with the parameters previously described. On the other hand, for the HTBW case, the materials were not welded when the solubilized process finished; at this stage, the materials were refrigerated at a temperature of 0 °C for 24 hours in order to prevent the material from naturally ageing [25-27]. In addition, for the HTBW process, after solubilized the materials, these were partially aged and brought to welding with an hour between partial ageing and welding. Concerning the heat treatments for the HTAW case, solubilize and total ageing were performed after the friction stir welding process, as shown in Figure 2(b).

Tensile Test, Microhardness Test and Electronic Microscopy.

The tensile and microhardness specimens were obtained from a section perpendicular to the weld, as shown in Figure 3(a). Figure 3(b) shows the dimension of tensile specimens and Figure 3(c) corresponding to microhardness specimens. The tension test were using Zwick / Roell Z100 universal machine with a maximum test load of 100 kN. Experiments were carried out at a constant speed of 6 mm/min, and the dimensions and tolerances were selected based on the ASTM-E8M standard. Micro-hardness profiles were obtained from HM 200 Mitutoyo micro-durometer, model at an applied load of 0.1 kg for 10 seconds. Furthermore, scanning electron microscopy analysis was carried out on the fracture zones of the tensile specimens, together with x-ray diffraction on the fracture zones.

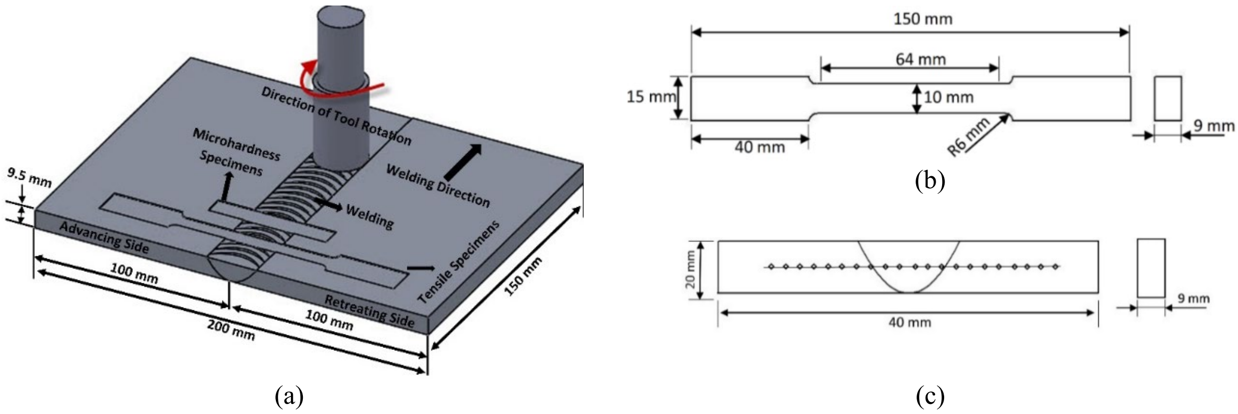


Figure 3. (a) Description of the FSW process and localization for tension and micro-hardness specimens. Dimension of (b) tensile and (c) microhardness specimens.

EXPERIMENTAL RESULTS

Microhardness

The microhardness profiles of the weld cross section for each case of study is shown in Figure 4(a). The four characteristic zones of friction welding with agitation are distinguished in Figure 4(b) which are agitation zone (stir zone), thermomechanical affected zone (TMAZ), thermally-affected zone (HAZ) and unaffected material (UFM) [28, 29]. From Figure 4(a), the micro-hardness at the stir zone were; 85 HV for the base material welded (BMW), 109 HV for the material with heat treatment before welding (HTBW), and 134 HV for the material with heat treatment after welding (HTAW). For the last case (HTAW), the micro-hardness presents the lowest dispersion showing values between 124 HV and 148 HV along the four characteristic zones as described previously.

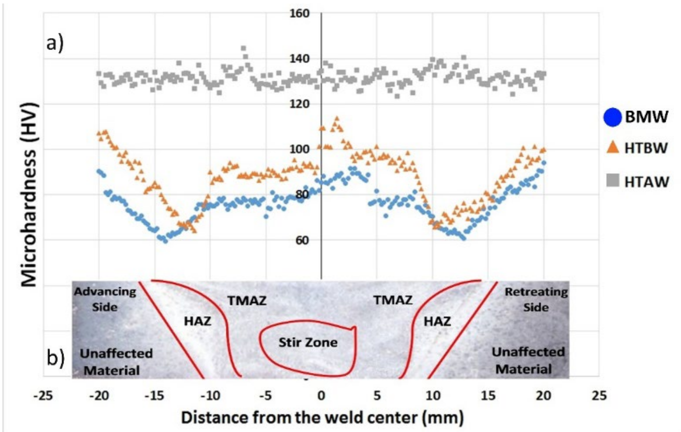


Figure 4. (a) Microhardness profile and (b) thermal welding profile.

Tensile Properties

A total of 21 tensile tests were carried out with six specimens for each case study and three samples for the base material. The tension strength for all tested specimens are shown in Table 3. The average tensile strength for each type of specimen was 170 MPa for the materials welded without any heat treatment (BMW). This value representing approximately 55 % of the tensile strength for the base material (310 MPa). Concerning the HTBW case, the average tensile strength increased to 202 MPa, which represents 65 % of the base material. Finally, for the HTAW heat treatment, the average tensile strength was 298 MPa, a value close to 96 % in regard to the base material [30]. From the fracture surfaces of tensile specimens, for the BMW and HTBW cases, most of the fractures occurred on the advance side of the tool and in the heat-affected zone as in Figure 5(a) and 5(b). On the other hand, fracture occurs on the unaffected material zone (UFM) and retreating side for the HTAW case (Figure 5(c)).

Table 3. Tensile strength for tested specimens.

Joints	Yield strength at 0.2%	Elongation (%)	Ultimate tensile stress (MPa)	Fracture side	UTS average (MPa)	Joint efficiency (%)
BMW-1	119	8.7	161	Advancing	170	54
BMW -2	116	5.8	172	Advancing		
BMW -3	115	9.0	176	Advancing		
BMW -4	116	4.3	169	Advancing		
BMW -5	115	9.6	171	Retreating		
BMW -6	116	10.0	176	Advancing		
HTBW-1	140	10.0	206	Advancing	202	64
HTBW -2	136	10.1	204	Advancing		
HTBW -3	140	10.2	203	Advancing		
HTBW -4	135	3.9	200	Advancing		
HTBW -5	142	4.5	201	Advancing		
HTBW -6	135	3.8	205	Retreating		
HTAW-1	273	3.9	295	Retreating	298	96
HTAW -2	277	1.5	289	Retreating		
HTAW -3	272	2.5	290	Retreating		
HTAW -4	305	1.0	309	Centre		
HTAW -5	279	2.8	299	Advancing		
HTAW -6	302	1.2	308	Advancing		
BM-1	289	14.2	309	----	311	------
BM-2	296	11.5	316	----		------
BM-3	286	14.2	308	----		------

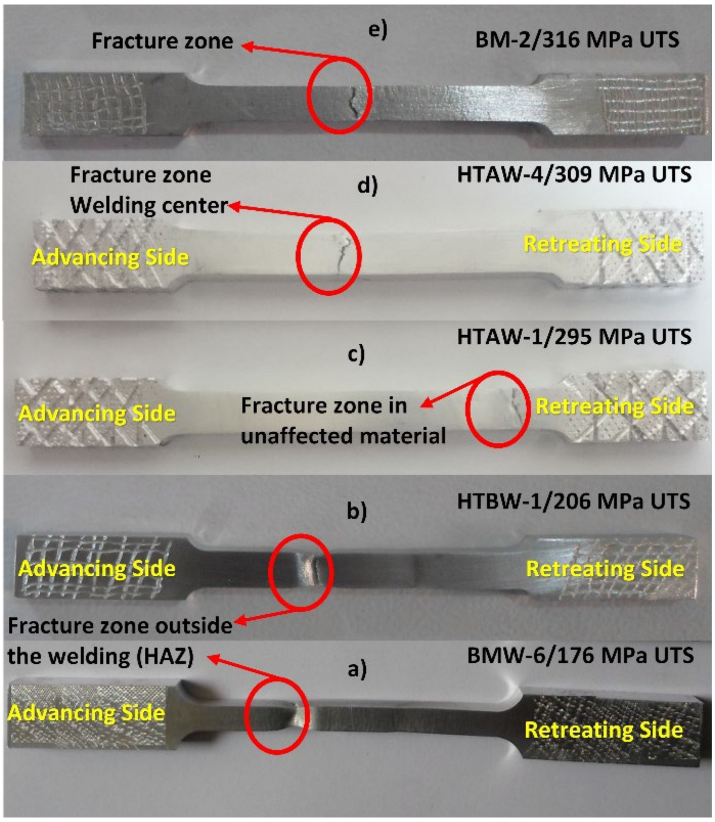


Figure 5. - Fracture zones under tensile tests for (a) BMW, (b) HTBW, (c), (d) HTAW and (e) base material.

One exception was observed for HTAW-4 specimen, for which fracture occured at the centre of the joint, fracture site similar to that occurring in the base materials shown in Figure 5(d) and 5(e) respectively. Figure 6 shows the lateral and frontal views of the test HTBW-1, with an ultimate tensile strength close to 206 MPa. This specimen was attacked chemically in order to enhance the fracture surface, which is located at the heat-affected zone (HAZ). As shown in Figure 4(a), micro-hardness for the welded specimens BMW and HTBW decreases to a minimum value inside HAZ, inducing higher ductility and low tensile strength at this zone [31]. The last behaviour leads to a similar zone of fracture for the BMW and HTBW specimens, even if the tensile strength is different for these two cases.

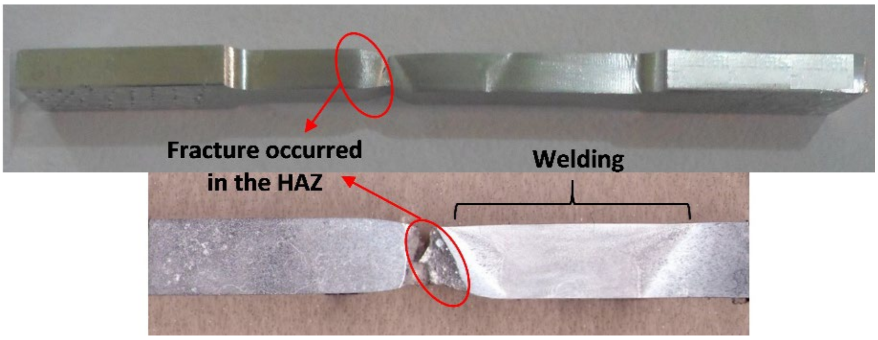
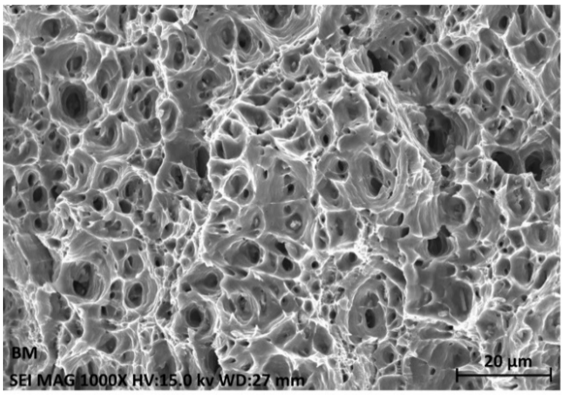


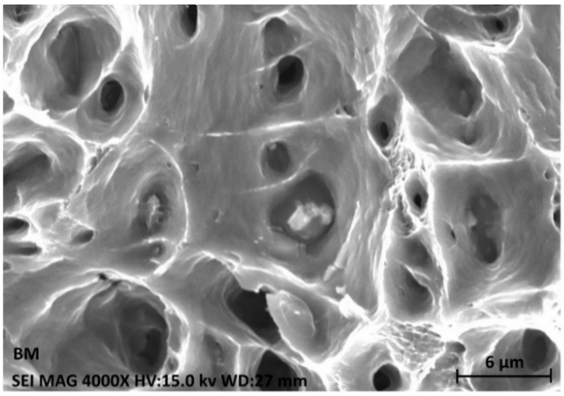
Figure 6. Fracture zone for HTBW-1 from tensile test.

Micrographic Analysis of Fracture Surfaces

The fracture surfaces of tension specimens for the three cases of study and the base material were analysed by scanning electron microscopy as in Figure 7(a) to 7(h). The micro-voids present in the fracture zones for the three cases BMW, HTBW and HTAW, reveal that fracture occurred due to ductile behaviour, generating micro-voids coalescence [32]. Figure 7(a) and 7(b) shows the fracture surface of the base material which presents micro-holes of 6-8 µm of diameter; whereas Figure 7(c) to 7(f) illustrated the cases of BMW and HTBW respectively, where the diameter of the micro-holes is bigger compared to the base material at approximately 8-10 and 10-12 µm. The last behaviour for BMW and HTBW cases can be explained by the fact that the nucleation sites were reduced and separated one of each other, allowing to grow at a larger size. Finally, for HTAW case, the micro-holes present small and shallow sizes, due to the fact that there were numerous nucleation sites causing merge of micro-holes, which leads to growth limit at a larger size (Figure 7(g) and 7(h)) [33].



(a)



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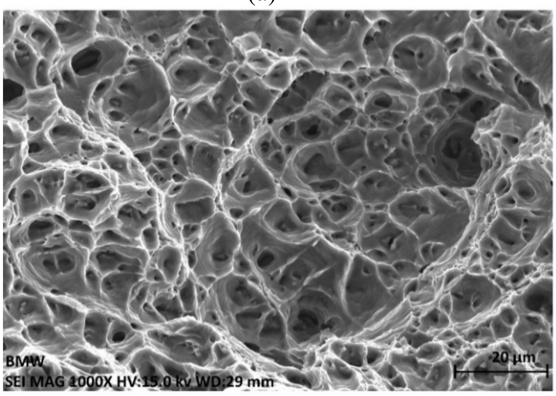
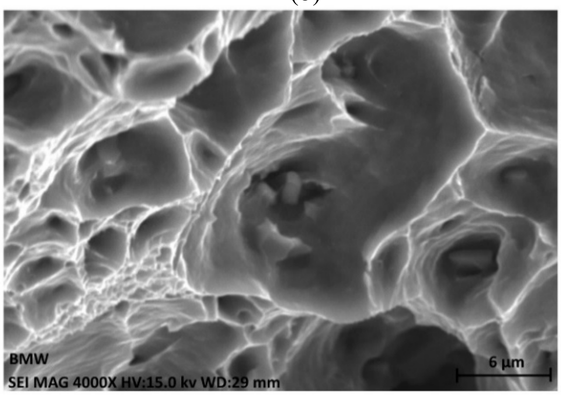


(c)



(d)

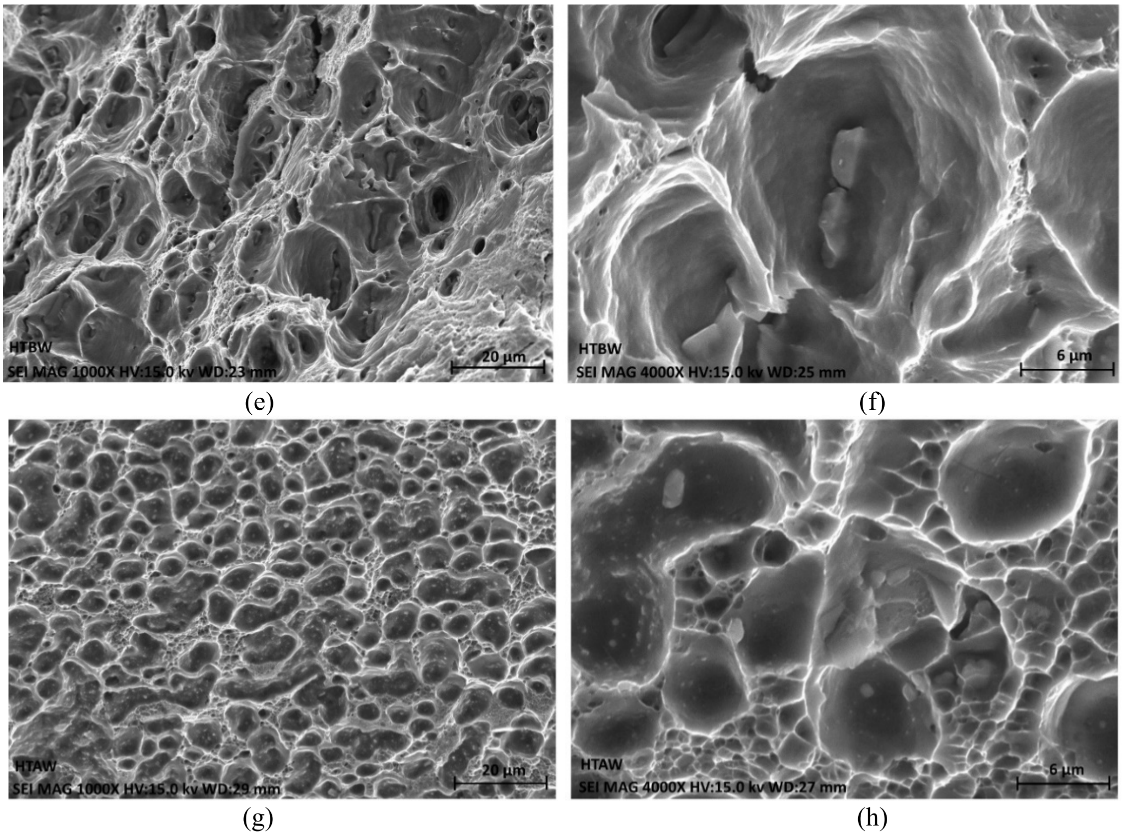


Figure 7. Fracture surfaces of tensile test for (a), (b) base material, (c), (d) BMW, (e), (f) HTBW and (g), (h) HTAW.

The 6061-T6 aluminium alloy has Mg-Si hardening elements that generate precipitates during heat treatments. Solubilized and partial ageing heat treatments were at origin for the formation and distribution of the precipitates in the material. Figure 8(a) to 8(d) show the EDS analysis corresponding to the composition of precipitates present in the base material and the three cases of study (BMW, HTBW, HTAW). The predominant precipitates for the BMW and HTBW cases were Al-Mg and Al-Si, respectively; while for the HTAW case it was found Fe-Mg_2-Si.

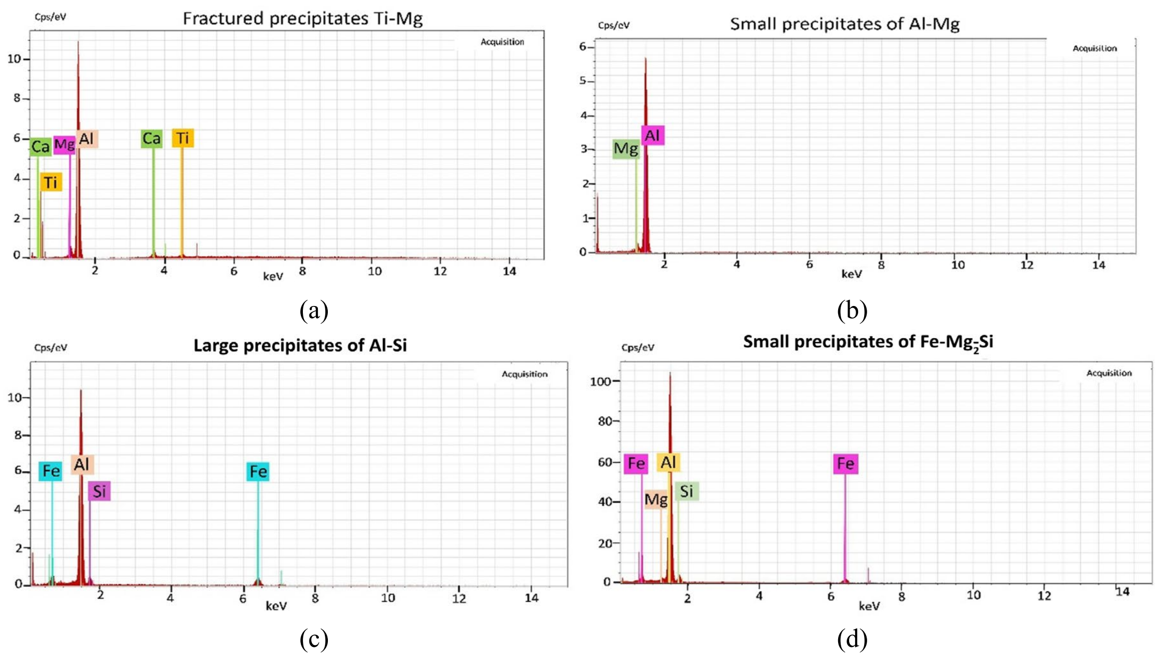


Figure 8. EDS analysis for (a) base material, (b) BMW, (c) HTBW and (d) HTAW.

DISCUSSION

The experimental tensile results allow to extract the principal trends of heat treatments: for the BMW case the tensile strength is lower compared to base material due to over ageing heat treatment which is generated by the thermal cycle during the friction stir welding process. For the case HTBW the tensile resistance is improved compared to BMW case, because the increase of precipitates, as shown in Figure 7(e) and 7(f). Furthermore, the heat treatment of partial ageing before welding coupled with the thermal cycle during welding may complete the ageing process of the material, even it may induce a reversing of the ageing process at the same time. Finally, for HTAW case, it was found that the tensile strength exceeds the values obtained for the BMW and HTBW cases, the tensile strength is close to that the base material. The last results may be explained by the higher number of precipitates and the smaller size of micro holes in this case, compared to BMW and HTBW (see Figure 7(g) and 7(h)).

On the other hand, the hardness found for the BMW case shows that there is a significant softening of the material compared to the base material. The cause of this hardness decay was due to the ageing of the material and the thickening of the precipitates, which were caused by the mechanical work and heat generation during welding process. For the HTAW case, the hardness obtained exceeds the base material; this was possible by a uniform distribution of precipitates in the zone of agitation inside the welded zone, combined with a smaller size of precipitates. The zone where the fracture occurred during the tensile tests was in the HAZ. This behaviour was observed for the BMW and HTBW cases, while the fracture in the last two cases was localised on the advance side of the tool.

CONCLUSION

The following conclusions can be drawn from the present research work:

i. The effects of tensile strength and microhardness on friction stir welded 6061-T6 aluminium were investigated under heat treatments; partial ageing during 6 hours and solubilized before welding, and total ageing for 6 hours and solubilized after welding.
ii. The tensile strength obtained for the BMW case equals the results obtained in joints by traditional means of fusion welding, but without excessive energy expenditure and less damage to the environment.
iii. The application of thermal treatment of solubilized at the first stage and then partial ageing before welding, improves the tensile strength by 10% compared to that obtained in BMW.
iv. For the HTAW case, the heat treatments after welding of solubilized at the first stage and then total ageing, leads to an efficiency of 96% of tensile strength compared to the base material. In addition, an increase in hardness of 24 HV is observed compared to the base material.
v. It should be possible to improve the results obtained for BMW and HTBW cases by modifying the parameters of the welding process (speed of rotation, translation speed, penetration speed and holding time).

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