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Comparison of TIG welded and friction stir welded Al–4.5Mg–0.26Sc alloy

A. Cabello Muñoz^a, G. Rückert^a, B. Huneau^{a,*}, X. Sauvage^b, S. Marya^a

^a Institut de Recherche en Génie Civil et Mécanique (GeM), UMR CNRS 6183, Ecole Centrale de Nantes, 1 rue de la Noë, BP.92101, F-44321 Nantes Cedex 3, France

^b Groupe de Physique des Matériaux (GPM), UMR CNRS 6634, Institut des Matériaux de Rouen, Université de Rouen, Avenue de l'Université, BP.12, F-76801 Saint-Etienne-du-Rouvray, France

This paper investigates the comparative microstructural and mechanical characteristics of fusion welds (TIG) and solid-state welds (FSW) of Al–4.5 Mg–0.26 Sc heat-treatable aluminium alloy. Microstructures of base metal and welded zones are analyzed by optical (OM) and transmission electron (TEM) microscopy. Particular emphasis is laid on the evolution of hardening precipitates in welded areas. The corresponding mechanical properties are evaluated through microhardness measurements and uniaxial tensile tests. The effect of a post-weld heat treatment on both microstructure and mechanical properties is further examined. The results suggest that hardening precipitates are comparatively more affected by the TIG than by the FSW process. This results in a substantial reduction of mechanical properties of TIG welds that can be partially recovered through a post-weld heat treatment.

Keywords:

Fusion welding
Activated TIG
Friction stir welding
Al–Mg–Sc alloy
Microstructure
Mechanical properties

1. Introduction

Heat-treatable Al alloys are largely used in aeronautical applications due to their excellent strength to density ratio, although they are difficult to weld by conventional fusion welding. Al–Mg–Sc alloys are based on Al–Mg alloys (5XXX series) in which small addition of scandium substantially improves their mechanical properties (Filatov et al., 2000). This addition of scandium, first proposed by Willey in 1971 (Willey, 1971), involves the formation of Al₃Sc particles during annealing as a result of the decomposition of the Al–Sc solid solution. The increase of strength results from both the precipitation of ordered Al₃Sc particles and the preservation of a fine grain structure (Zakharov, 2003; Nieh et al., 1997). Indeed,

high volume fraction and high dispersivity of these particles in the matrix promote a noticeable elevation of the recrystallization temperature of wrought Al–Mg–Sc alloy semiproducts (Filatov et al., 2000). This allows keeping the initial strain hardening benefits even after annealing at rather high temperatures.

The thermal stability of Al₃Sc particles is very high (melting point of Al₃Sc: 1320 °C) (Murray, 1998) and the misfit in lattice parameter between Al and Al₃Sc is only 1.3% in binary Al–Sc alloys (Iwamura et al., 2002), which makes these particles stable against coarsening up to 350 °C (Marquis and Seidman, 2001). Moreover, some authors have established that the presence of Mg in the aluminium matrix improves the coherency of Al₃Sc particles by about 30%, increasing the critical radius

Table 1 – Chemical composition (wt.%) of the Al-Mg-Sc alloy

Mg	4.58
Sc	0.26
Mn	0.08
Zr	0.09
Fe	0.1
Si	0.28
Al	Bal.

for the coherency/incoherency transformation (Iwamura et al., 2002).

The present paper compares the influence of a fusion welding technique (TIG also called GTAW) and a solid-state welding technique (FSW) on both microstructure and mechanical properties of an Al-Mg-Sc alloy.

In TIG welding, an electric arc is formed between an inconsumable tungsten electrode and the workpiece. The arc provides the thermal energy to melt the workpieces as well as the filler if necessary. For Al alloys, due to their elevated thermal conductivity, the weld penetration remains very shallow: less than 3 mm in one pass. To enhance the penetration, activated TIG technique (A-TIG) is used. A-TIG process is a TIG modification where a coating, composed of oxides or halides, is applied on the top surface adjacent to the weld joint before welding (Lucas and Howse, 1996). Two mechanisms are generally reported to describe the action of activating coating: the arc constriction by negative ions (Simonik, 1976) and the thermocapillary flow inversion in the weld pool (Heiple and Roper, 1982). The elevated temperatures attained in fusion welding processes induce an important microstructural evolution especially concerning hardening precipitates.

Friction stir welding (FSW) is a solid-state joining technology patented by The Welding Institute (TWI) in 1991 (Thomas et al., 1991, 1995). This process involves the advance of a rotating hard steel pin extended by a cylindrical shoulder between two contacting metal plates. Frictional heating is produced from the rubbing of the rotating shoulder with the two workpieces, while the rotating pin deforms the heated material. Compared to fusion welding processes, there is little or no porosity or other defects related to fusion. However, the hardening precipitates responsible for the good mechanical properties of heat-treatable Al alloys (2XXX, 6XXX and 7XXX series) are shown to be very affected by this process, partly because of their low stability (Genevois et al., 2005; Murr et al., 1998; Rhodes et al., 1997).

In fact, the industrial interest of this study is to evaluate the possible benefits of FSW compared to A-TIG, considering the lower heat input of the solid-state joining process and the high stability of hardening particles.

2. Experimental

Rolled plates of an Al-4.5Mg-0.26Sc alloy of 4 mm thickness are supplied in the condition H116 and their chemical composition is given in Table 1. These plates were fusion welded using A-TIG technique and friction stir welded. To accomplish A-TIG welds, two strips of SiO₂ coating are applied on each side of the weld line (Sire and Marya, 2002); the other parameters of the

Table 2 – Fusion welding conditions (A-TIG)

Welding current (A)	100
Welding speed (mm/s)	4.2
Arc length (mm)	2
Shielding gas	Helium
Gas Flow (l/min)	14
Coating	SiO ₂

process are given in Table 2. The friction stir welds were performed using a conventional milling machine; the rotational speed was 500 rpm and the weld travel speed 1 mm/s. In both cases the welding direction coincided with the rolling direction. Samples were cut perpendicular to the welding direction and some of them were subjected to heat treatment at 300 °C during 1 h and air cooled.

Microstructure was characterized using optical microscopy (OM) and transmission electron microscopy (TEM). Metallographic specimens were prepared by conventional polishing followed by chemical etching for optical metallography. TEM specimens were prepared in the cross-section of the welded sheets. Discs were cut with a drilling machine and mechanically thinned down to 100 μm. The electron transparency of the specimens was achieved with a twin-jet electropolisher, using a 1/3 HNO₃ and 2/3 methanol solution at -30 °C with a voltage of 13 V. TEM observations were performed with a JEOL 2000FX microscope operating at 200 kV.

Vickers microhardness measurements were carried out under 2000 mN load in the transverse cross-section of the joints by using a Fisherscope® HM2000. Tensile tests were carried out for welded and heat-treated samples as well as for base metal (BM). All the tensile samples have a 4 mm × 10 mm × 50 mm gauge length and were tested at failure with a constant crosshead speed (27 mm/min).

3. Results

3.1. Base metal

The base metal of Al-4.5Mg-0.26Sc alloy is characterized by pancake microstructure. As shown in OM and TEM micrographs of Fig. 1a and b, the highly deformed grains are elongated in the rolling direction with a length in a range between 1 and 10 μm and a thickness smaller than 500 nm. The strain field contrasts marked with black arrows in the bright field image of Fig. 1c shows the existence of coherent Al₃Sc particles; their presence is confirmed in the diffraction patterns as a superlattice reflection, marked with a white circle in Fig. 1d. Fig. 1e is the dark field image corresponding to Fig. 1c obtained when the superlattice reflection is selected. The size of the coherent Al₃Sc particles is in a range from 5 to 15 nm. Incoherent Al₃Sc inclusions were also found with a bigger size close to 30 nm.

3.2. Weld structures

The centre of the friction stir weld is composed by the nugget and the flow arm (Fig. 2a), both exhibiting recrystallized equiaxed grains with a few microns in size (Fig. 2b). As in the

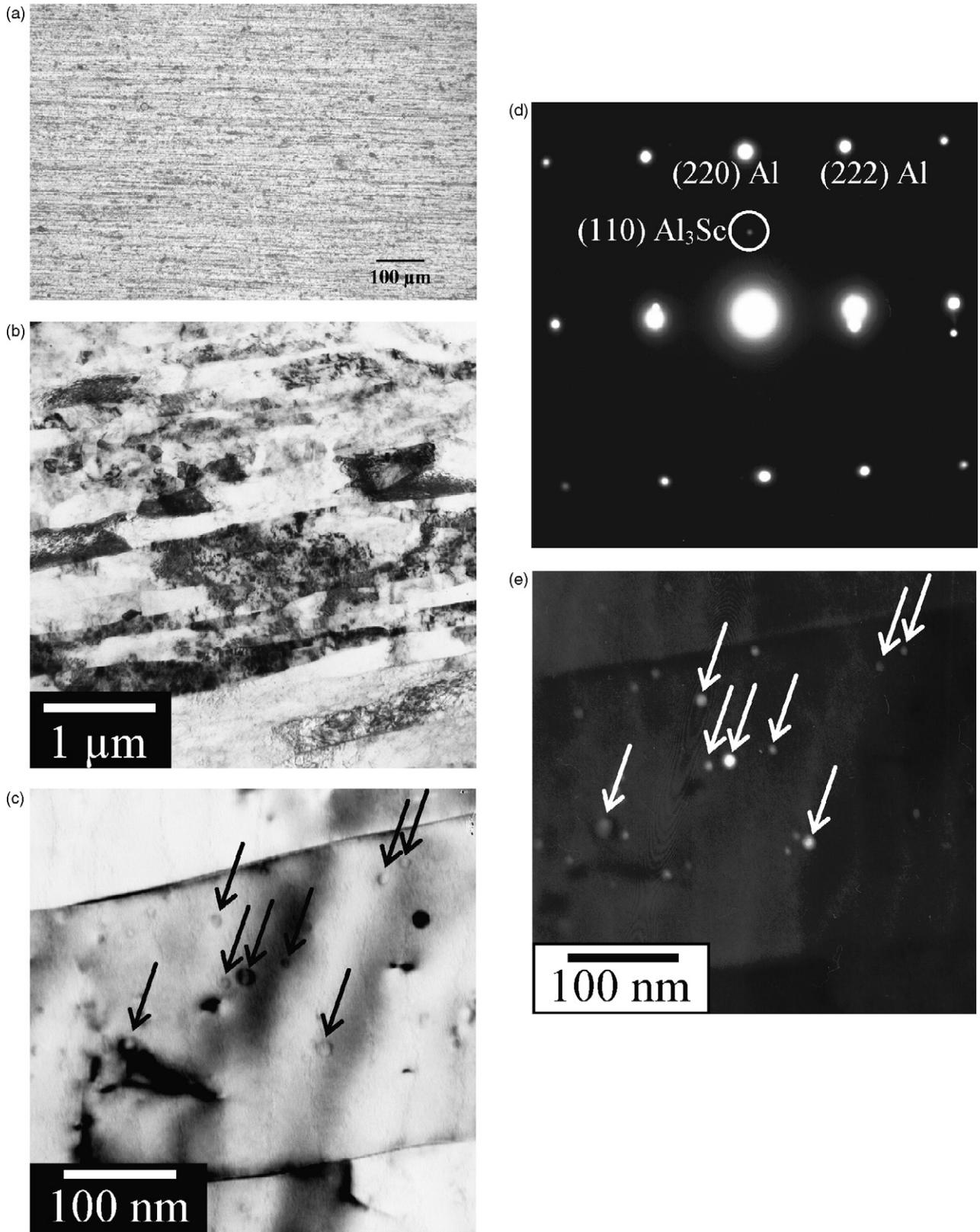


Fig. 1 – (a) Optical micrograph of BM, (b) bright field TEM micrograph of BM, (c) same zone at higher magnitude with coherency strain field contrasts (black arrows), (d) diffraction pattern of this zone with Al₃Sc streak (white circle), and (e) dark field image of (c).

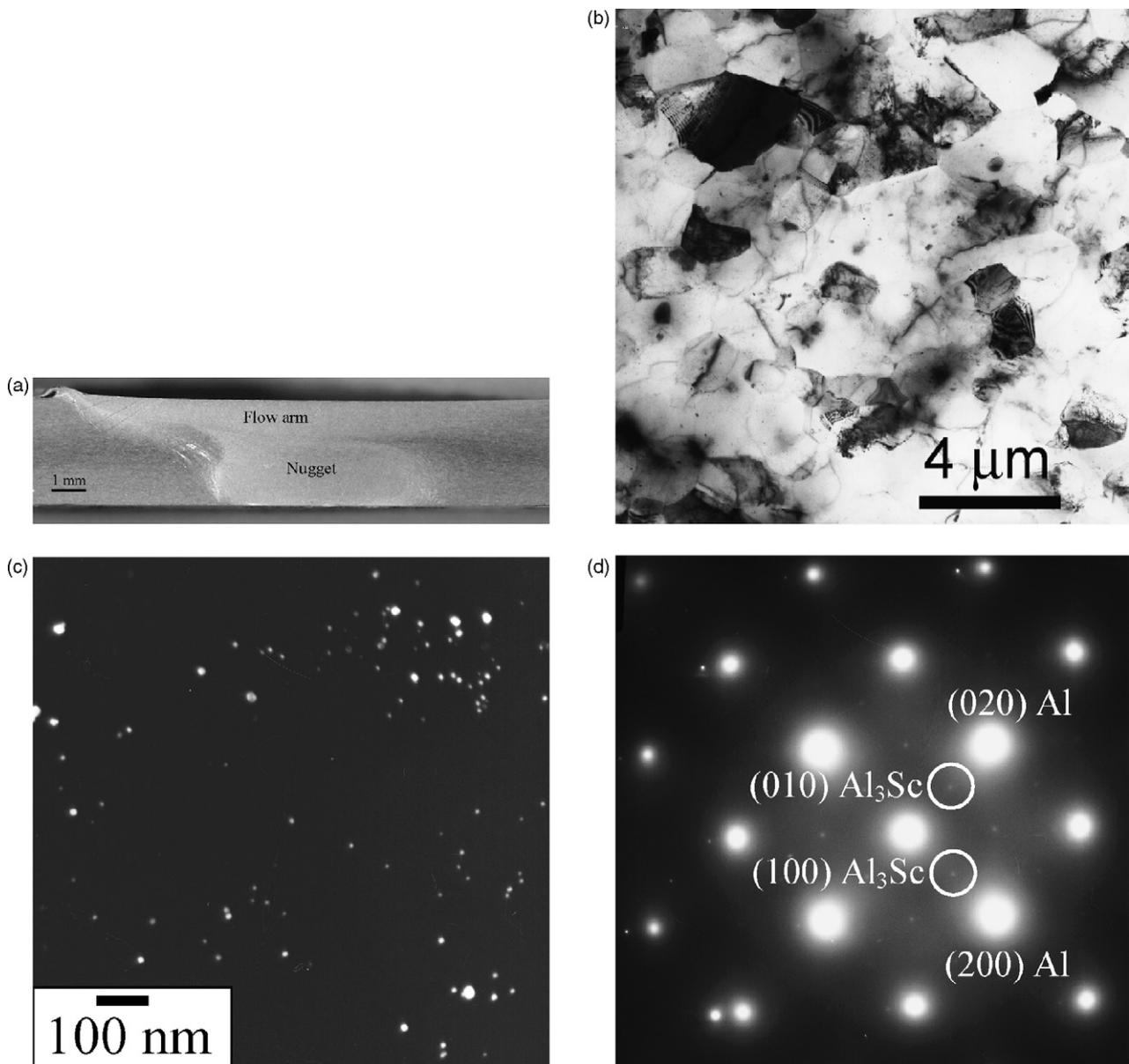


Fig. 2 – (a) Macrograph of FSW cross-section, (b) bright field TEM micrograph of the nugget zone, (c) dark field of the nugget with Al_3Sc particles and (d) diffraction pattern with superlattice Al_3Sc streaks.

BM, Al_3Sc nanometric coherent and incoherent particles were identified in TEM examinations of the recrystallized grains (Fig. 2c). The superlattice diffraction pattern produced by the coherent particles is clearly seen in Fig. 2d.

A-TIG molten zone and HAZ are shown in optical micrograph of Fig. 3a. The microstructure of solidification zone appears relatively fine especially in the centre of the weld as presented in Fig. 3b. In this case, no Al_3Sc precipitates were found in the molten zone. But, after a heat treatment consisting in 300°C heating during 1 h, Al_3Sc coherent precipitates were observed in A-TIG weld as shown by the diffraction pattern of Fig. 3c. They are spherical in shape with a diameter between 5 and 15 nm. No incoherent precipitates were detected in this case.

For FWS and A-TIG as welded specimens, complementary SEM and EDX analysis performed in the welded areas show

that Mg content is the same than in BM and that no inclusions rich in Mg are present.

3.3. Hardness profiles

For both processes, microhardness profiles plotted on Fig. 4a and b demonstrate that the centre of the joints is the weakest zone of the as-welded structures. The hardness decrease is much smaller in FSW nugget compared to A-TIG molten zone. Considering that base metal hardness is around 130 HV, this decrease is around 27 HV in the case of FSW (Fig. 4a) and almost 60 HV in the case of A-TIG (Fig. 4b).

After heat treatment (300°C during 1 h), hardness of the zones unaffected by welding operations decreases from 130 to 120 HV for both processes (Fig. 4a and b). In A-TIG molten zone, hardness highly increases and reaches the same aver-

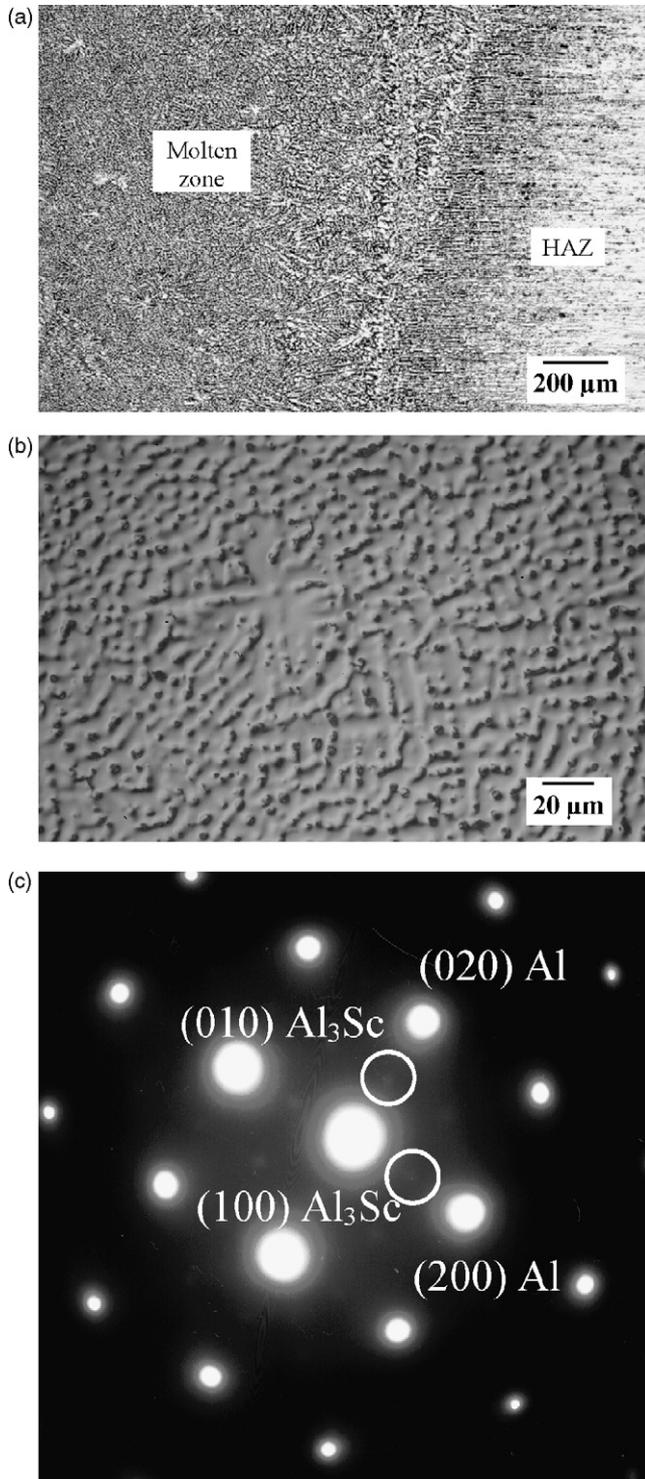


Fig. 3 – (a) Optical micrograph of A-TIG molten zone and HAZ, (b) optical micrograph at higher magnification of the molten zone at the weld centre and (c) diffraction pattern of heat-treated A-TIG weld centre with streaks of coherent Al_3Sc precipitates.

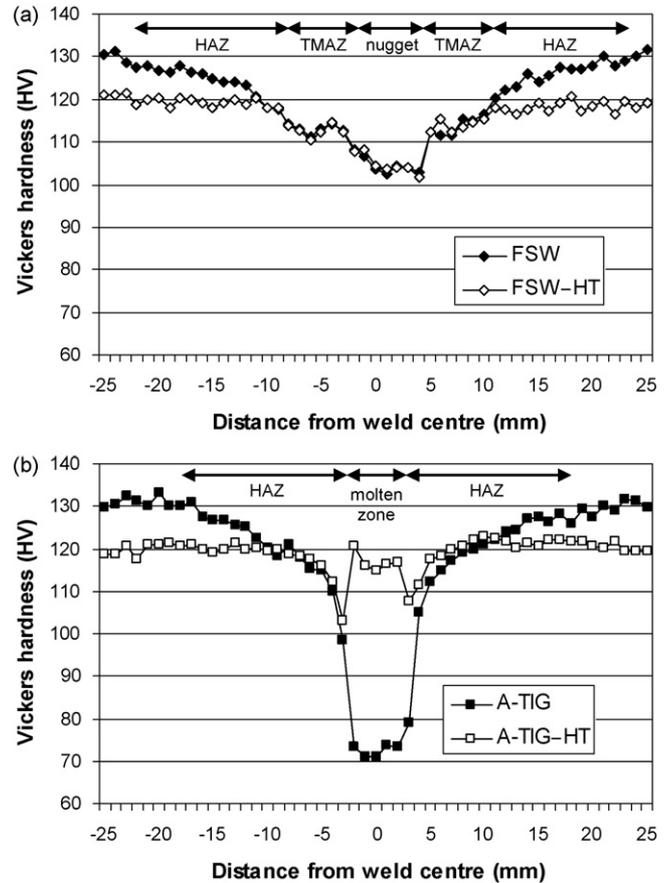


Fig. 4 – Hardness profiles of cross weld sections (a) as-welded FSW and heat-treated FSW (denoted FSW-HT) and (b) as-welded A-TIG and heat-treated A-TIG (denoted A-TIG-HT).

age value of 120 HV (Fig. 4b). For this process, the smallest hardness values are located at 3 mm from the centre which corresponds to HAZ near the molten zone. Heat treatment appears to have no effect on the hardness of FSW nugget and thermo-mechanically affected zone (TMAZ) (Fig. 4a).

3.4. Tensile tests

To complement previous hardness results, uniaxial tensile tests were carried out on BM, welded joints and heat-treated joints. All samples broke in the weld except for heat-treated A-TIG samples for which fracture occurs in HAZ close to the molten zone. Resulting yield strength (YS) and ultimate tensile strength (UTS) are presented in Fig. 5.

Both YS and UTS are affected by welding operations but more significantly for A-TIG process. The decrease of YS between FSW joint and BM is about 20%, whereas it is almost 50% between A-TIG joint and BM. Moreover, post-welded heat treatment improves YS and UTS especially in the case of A-TIG.

4. Discussion

Previous results clearly demonstrate that mechanical properties of fusion welds are more lowered than those of friction stir

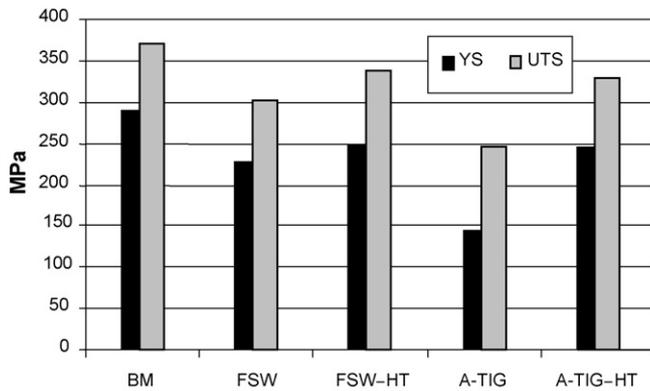


Fig. 5 – Mechanical properties of base metal and welded zones with and without heat treatment.

welds for the present Al-4.5Mg-0.26Sc alloy. Before discussing the effect of both processes on the changes of microstructure and mechanical properties, it should be recalled that the strength of BM is mainly due to Al-Mg solid solution, strengthening by Al₃Sc particles and strain hardening consecutive to rolling operation. It should be noted that the fine pancake microstructure is preserved during annealing because of both Zener pinning of grain boundaries and high-thermal stability of Al₃Sc particles, which prevent recrystallization (Marquis and Seidman, 2001).

First, it is assumed that the contribution of Al-Mg solid solution to alloy strength is not significantly affected by both welding processes. Indeed, Mg content is not lower in welded zones than in BM and no inclusions or precipitates containing Mg were detected in welded areas. This assumption is supported by previous studies on a 5086-H111 alloy that derives its strength mainly from Mg solid solution, and for which hardness of welded zones was not affected neither by FSW nor by A-TIG processes (Cabello-Munoz, 2005).

In the present study, FSW nugget exhibits a fine recrystallized grains microstructure as well as fine-dispersed Al₃Sc hardening precipitates. Even if no quantitative volume fraction analysis of these particles was performed, their size and shape as well as their distribution are not highly different than those observed in BM. The emphasis must be laid on this result because hardening precipitates in other heat-treatable Al alloys are generally very affected by the FSW process, which involves a strong decrease of mechanical properties (Genevois et al., 2005; Murr et al., 1998; Rhodes et al., 1997). For example, Murr et al. (Murr et al., 1998) reported a loss of 50% in hardness of FSW joints for 6061 aluminium alloy when compared to BM. Consequently, the decrease of mechanical properties from BM to FSW (20% for YS) observed for the present Al-4.5Mg-0.26Sc alloy can be considered as limited. This decrease is assumed to be due to a loss of strain hardening related to recrystallization and a modification of hardening precipitates, part of them being probably dissolved. These results are in good agreement with previous studies of Lapasset et al. (Lapasset et al., 2003) and Huneau et al. (Huneau et al., 2005).

For A-TIG process, the situation is comparatively simpler. The important softening observed in the welded zone is

due to a loss of strain hardening associated with fusion and above all to the absence of Al₃Sc precipitates because of their dissolution during the melting phase. This dissolution was expected because of the high temperatures attained during A-TIG welding.

For both welding processes, samples which were subjected to a 300 °C heat treatment during 1 h exhibit a small hardness decrease in the zone unaffected by welding operations which is assumed to be related to a loss of strain hardening compared to the initial BM. If the effect of this post-weld heat treatment is not significant on FSW welds, it has a strong effect on the mechanical properties of A-TIG welds because it allows Al₃Sc particles to reprecipitate. It is interesting to note that hardness of molten zone reaches the same value than the zone unaffected by the process (120 HV). It first suggests that the precipitation state obtained for these conditions is close to the optimal state of BM. Secondly it means that the influence of grain structure appears of less importance even if the contrary was expected. Indeed the solidification structure which is very different from the pancake structure of BM exhibits yet the same hardness. The fineness of the solidification structure could explain this point. Thirdly, reprecipitation seems to be easier from a supersaturated solid solution without any precipitates, i.e. in the molten zone, than from a state where the precipitates are supposed to be partially dissolved or modified, i.e. in FSW nugget and TMAZ as well as in A-TIG HAZ near the molten zone.

Finally, heat-treated samples for A-TIG or FSW techniques have more or less the same mechanical properties in terms of YS and UTS even if hardness is higher in the centre of the weld in the case of heat-treated A-TIG samples. This is due to the smaller mechanical resistance of HAZ where the fracture occurs and whose hardness is comparable to the one of heat-treated FSW nugget.

5. Conclusion

The influence of two joining methods, i.e. fusion (TIG) and solid-state (FSW) welding processes, on both microstructure and mechanical properties of Al-4.5Mg-0.26Sc alloy was investigated.

It appears that FSW joints exhibit higher mechanical properties than those obtained by A-TIG. Compared to base metal, YS of welded joints decreases by 20% for FSW and 50% for A-TIG. This decrease is explained by a loss of strain hardening and a modification of Al₃Sc hardening particles. The difference between friction stir welds and fusion welds is explained by a partial preservation of Al₃Sc hardening particles in the case of FSW and a complete dissolution in the case of A-TIG.

A post-weld heat treatment at 300 °C during one hour strongly increases A-TIG welds mechanical properties because of the reprecipitation of hardening particles in the molten zone. The solidification structure does not seem to lower the mechanical properties of the joints. The same heat treatment has little or no effect on the FSW joints mechanical properties.

From industrial perspectives, it is well known that FSW process is very competitive because it saves energy and

prevents the joints from fusion-related defects. Moreover, it was demonstrated here that a post-weld heat treatment on FSW welds can eventually be avoided which is impossible when a fusion welding process such as A-TIG is used.

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