MECHANICAL AND MICROSTRUCTURAL CHARACTERISATION OF AN ALUMINUM FRICTION STIR-WELDED BUTT JOINT

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Abstract

The microstructure and the mechanical properties of a 6056 aluminium alloy Friction Stir-Welded (FSW) joint were investigated in the present study. The structure was analysed using light, scanning and transmission electron microscopy. The change in microstructure across the welded joint was found to correspond to significant variation in hardness. As in most FSW joints, the structure was characterised by the presence of a region of severely deformed grains in proximity of the weld nugget, i.e. of a region of fine recrystallised grains. Tensile tests showed that the joint material exhibited a rupture strength similar to the parent material, even though the former was significantly less ductile. This difference resulted in a reduction in ductility of the welded sheets. A T6 treatment increased tensile strength, but further reduced joint ductility. Nevertheless, the strength of the welded sheet was found to be very close (80-90%) to that of the base alloy.

Riassunto

Il presente studio ha preso in esame la microstruttura e le proprietà meccaniche di un giunto in lega di alluminio 6056 prodotto per Friction Stir Welding (FSW). La microstruttura è stata analizzata tramite microscopia ottica ed elettronica in scansione e trasmissione. Si è osservato che la variazione della microstruttura trasversalmente alla saldatura corrispondeva a significativi cambiamenti del valore della microdurezza. La microstruttura, come del resto usuale in giunti prodotti per FSW, era caratterizzata dalla presenza, in prossimità della zona indicata come "weld nugget", cioè della zona di grani ricristallizzati, di una regione in cui i grani erano severamente deformati. Le prove di trazione hanno mostrato che il materiale del giunto possedeva una resistenza a rottura abbastanza simile a quelle della lega madre, anche se era significativamente meno duttile. Un tale risultato si traduceva quindi in una complessiva riduzione della duttilità dell'insieme delle lamiere saldate. Un trattamento T6 aumentava la resistenza meccanica, a spese di ulteriori riduzioni della duttilità. Nondimeno, la resistenza delle lamiere saldate rimaneva molto prossima (89-90%) a quella del materiale base.

INTRODUCTION

Aluminum alloys are widely used to produce aerospace components with high specific strength. On the other hand, when traditional welding processes are applied to these alloys, they often entail disadvantage that have sometimes discouraged the use of welded components. Friction stir welding (FSW) is a recent method of joining materials patented in 1991 by TWI [1-13]; this process was developed from the classic friction welding methods and has the advantage of operating in solid state. In conventional friction welding the plasticized material is constrained in two dimensions (vertical and horizontal), while in FSW the layer of plasticized material is constrained in three dimensions [14]. FSW assures the absence of porosity, distortion and residual stresses, which are typical defects of the fusion welding processes, and the possibility to operate in all positions without protective gas. Alloys difficult to weld like the 2000 and 7000 series have successfully been welded using FSW. The process uses a shouldered rotating tool with a profiled pin that penetrates the clamped parts to be joined; the tool then starts to move along the join line (Fig.1). The heat produced by friction softens the alloy and the pin stirs the material of the joint until the sheets are joined. The stirring of one material into the other is associated with a solid-state flow, i.e. with a very high deformation, and involves recrystallisation of a portion of the joint (weld nugget). These extremely fine recrystallised grains are known to slide one over the other [8], leading to a superplastic flow that accommodates the FSW process. FSW temperature decreases from the top to the bottom of the joint, a change that corresponds to a variation in recrystallised grain size. The present study aims at characterising a friction stir-welded joint from the microstructural and mechanical points of view. To do this, specimens in as-welded, welded and aged conditions were investigated using different testing methods.

EXPERIMENTAL DETAILS

The joined sheets measured 200x470x4 mm; the material, a 6056-T4 alloy, had the following chemical composition (wt.%): 07-1.3 Si, 0.3-1.0 Mn, 06-1.2 Mg, 0.25 Cr, Cu=0.5-1.1, Zn=0.1-0.7.(Ti+Zr)=0.2, Fe=0.5, Al=bal.
Scanning Electron Microscopy (SEM) was used to analyse the friction stir-welded surface, i.e. the upper surface in Figure 1; upper and cross-sections were grinded, polished, etched with Keller's reagent (20 sec), and examined by light microscopy (LM). Vickers microhardness was measured along the weld on the same surface.
Samples for Transmission Electron Microscopy

(TEM) were cut from the central region of the weld to observe the microstructure of the severely deformed zone and the weld nugget. Thin foils were mechanically thinned to a mean thickness of 50-60 µm and treated with an electropolishing double jet with a solution of 25% HNO_3 in methanol at 18V and –35°C. TEM micrographs were taken with a Philips CM200 microscope equipped with double-tilting specimen holder. Tensile tests were carried out on specimens of different dimensions drawn from different locations (Fig. 2) to measure the mechanical properties of base, as-welded and T6-treated materials. The grey specimens in Figure 2 were subjected to ageing treatment, whereas the white ones were tested as-welded. Small samples were used to estimate the mechanical properties of the joint and large ones to evaluate the overall mechanical behaviour of the welded sheets.
Post-weld heat treatment consisted in solutioning at 530°C for 4 h and ageing. The base material was first aged for different times at 160°C and 175°C to identify the peak ageing condition.

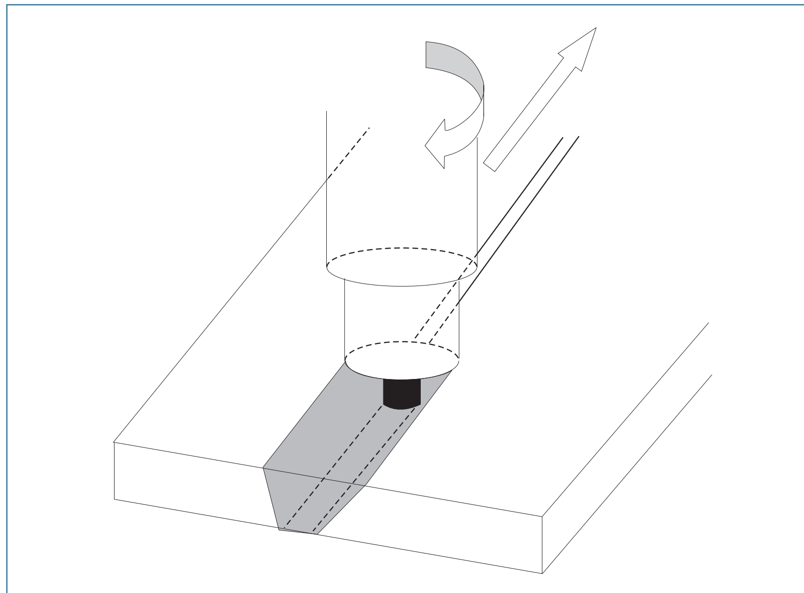

Fig. 1: Schematic representation of Friction Stir Welding process. The head of the rotating pin is in black. The grey zone represents the weld

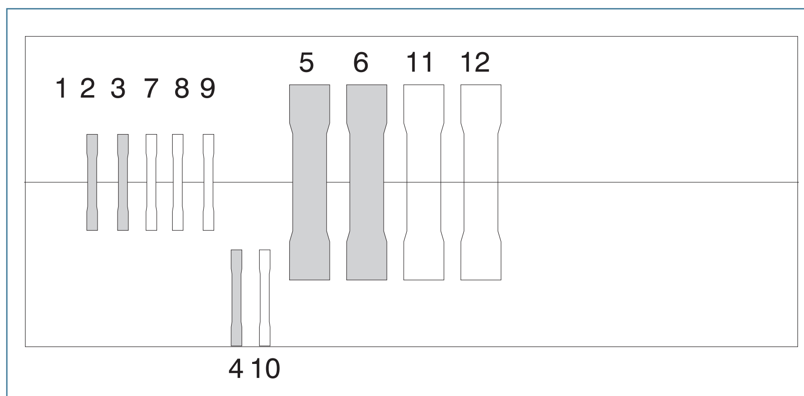

Fig. 2: Identification of tensile test samples: small specimens had a gauge length of 25 mm, and a 5x4 mm section; large samples had a 55 mm gauge length and a 20x4 mm section

Results and discussions

Figure 3 shows a SEM image of the upper surface of the joint, where tool and sheet were in contact. The roughness of the surface after welding can easily be distinguished (recent studies mention the possibility of using radially located cutters on the welding tool to reduce this effect [2]).
Figure 4 shows the macrostructure of the transverse surface across the welding zone. The cross-section has the typical aspect of a friction stir-welded zone, whose most prominent feature is the presence of a "weld nugget zone" characterised by fine equiaxed recrystallised grains. As mentioned above, the presence of this zone is due to the recrystallisation occurred during the welding. Figure 5 shows the microstructure of the weld. The difference in grain shape and dimensions between the weld nugget (Fig.5b) and the parent material (Fig.5c) is quite evident: the mean value of the grain size as measured by LM is 11 µm in the weld nugget and 65 µm in the parent alloy. Microstructure variations are also evident on the upper surface, where fine grains along the welding line are easily distinguished.
Microhardness tests along the welded joint (Fig.6) showed the relationship between microstucture and mechanical properties. For the cross-section, the hardness values are closely connected with the nature of the process experienced by the

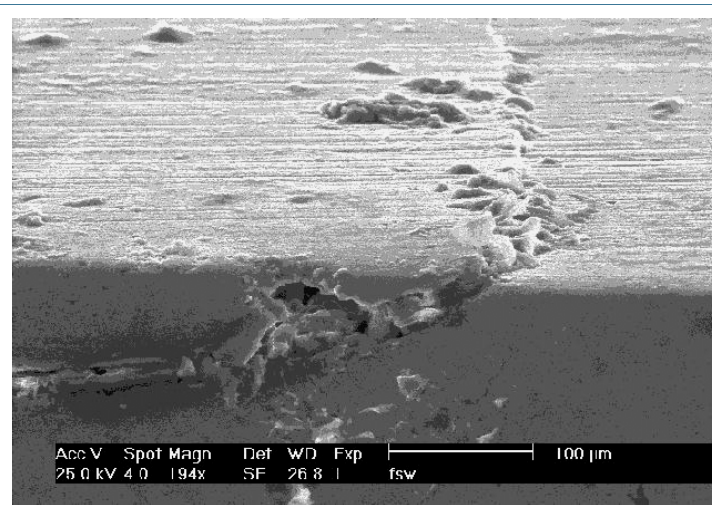

Fig. 3: SEM micrograph of the FS-welded zone

zones. In FSW aluminium joints four zones exist: the recrystallised central region (Fig.5b) surrounded by the thermomechanically affected zone (TMAZ), a heat affected and deformed region (Fig. 5a) and the heat affected zone (HAZ) on either side of the joint [14]. FSW creates a softened region around the weld center in precipitation-hardened Al-alloys [15]; the analysis of hardness distribution in the weld led indeed some authors [16] to conclude that the hardness profile in particle-hardened materials is mainly governed by the distribution of fine precipitates. The lowest hardness value in Fig.6 is found in an area of great grain distortion, indicated as "A" in Figure 4. A peak in hardness is observed in the central part of the weld-nugget; then, HV gradually decreases, reaches a minimum value in the heat-affected zone, and gradually increases up to the value typical of the parent alloy.

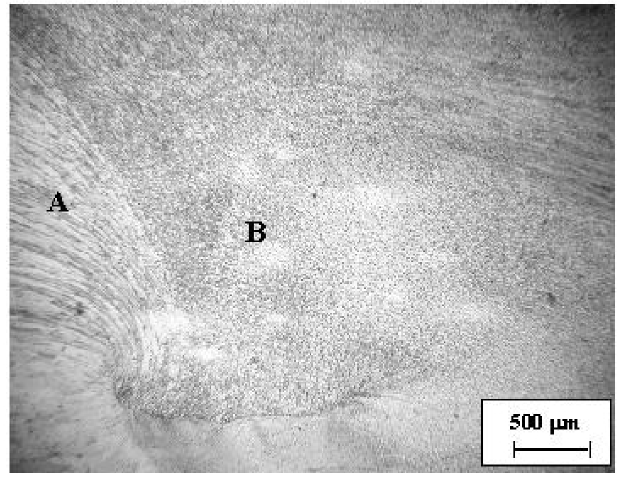

Fig. 4: Structure of the thermo-mechanical affected zone

Figure 7 shows the microstructure of the region of transition between weld nugget and non-recrystallised stirred material (Fig.7a) and the typical microstructure of the weld nugget interior. A dramatic difference in dislocation density between recrystallised and non-recrystallised grains is apparent. The grain interior is heavily decorated with intragranular Mg_2Si precipitates, which are extremely effective in reducing dislocation mobility, as clearly indicated by the high fraction of dislocations pinned on these precipitates. The low dislocation density in the recrystallised grains is well documented in Figure 7b. The fine grain size in the weld nugget can easily be appreciated; in particular, TEM analysis demonstrates that the average grain size obtained with LM measurements is overestimated. The size and distribution of intragranular precipitates do not change appreciably in the recrystallised region.

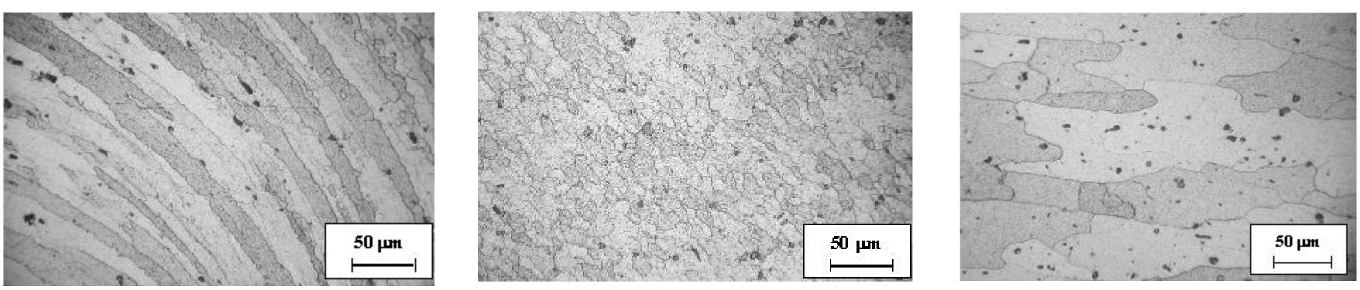

Fig. 5: Microstructure corresponding to the A (a) and B (b) zones in TMAZ. In (c) the structure of the parent material is shown

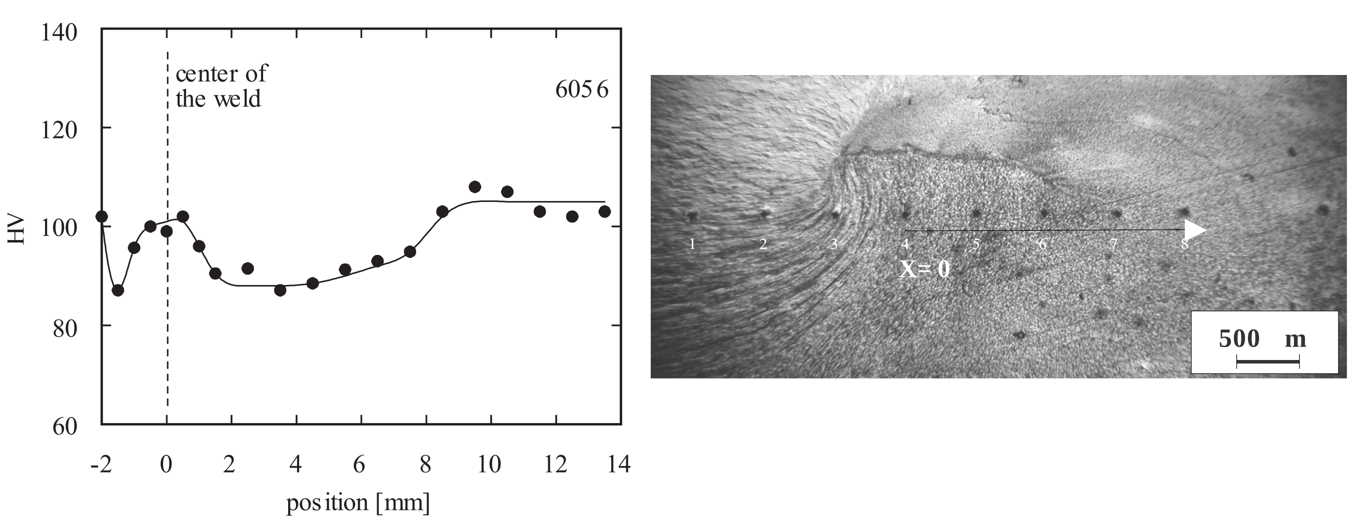

Fig. 6: a) Hardness profile along the weld (transverse section); in b) the microstructure and the x = 0 position are clearly shown

Ageing curves at 160°C and 175°C are shown in Figure 8. Analysis of this figure allowed to identify the conditions for T6 treatment (solution treatment at 530°C for 4 h and artificial ageing at 175°C for 24 h). Figure 9 shows the typical microstructure of the weld nugget after T6 treatment. The grain growth that took place during solution treatment is evident in Figure 9a. Figure 9b permits to appreciate the distribution of Mg_2Si precipitates after ageing.

Figure 10 shows some of the stress-strain curves obtained in this study. The parent material is very ductile even in the T6 condition; by contrast, the small samples machined from the joint are characterised by a low ductility. The T6 condition enhances this brittleness, with minor advantages in terms of tensile strength. The strain to fracture of the large transverse samples is thus lower than that of the parent material, an obvious effect of the relatively poor ductility of the joint. Nevertheless, the mechanical response of the welded sheets in terms of tensile strength and yielding is 80-90% of that of the parent material. Figure 11 summarised the averaged results of tensile tests. The variation in strength illustrated in Figure 11 are fully consistent with other literature data on 6000 alloys [17]. Also in the case of a 7075 alloy, the as-welded strength and ductility were found to be lower than those of the base material, that was characterised by the presence of precipitates of various sizes [18]; a post-weld heat treatment further reduced ultimate strength and ductility. This observation, and the fact that the tensile samples fractured in the region of the HAZ that experienced temperatures between 300 and 350°C during the welding process, led the authors to conclude that also in this alloy the mechanical response of FSW joint was controlled by the size and distribution of precipitates.

The study of the fracture location showed that in as-received specimens the failure began from the transition zone of the cross-section (Fig.5a), a result that again is fully consistent with the available data [14] that indicate that fracture do not occur in the weld nugget or in the joint centerline. By contrast, in T6 samples sometimes the fracture originated from the joint line, probably due to a greater concentration of precipitates in that zone after heat treatment, even if a recent study [19] suggested that, in the case of a solution treated and aged joint, the fracture should occur in the region with the minimum average Taylor factor, i.e. the fracture location depends on crystallographic-orientation distribution and strain tensor of imposed deformation.

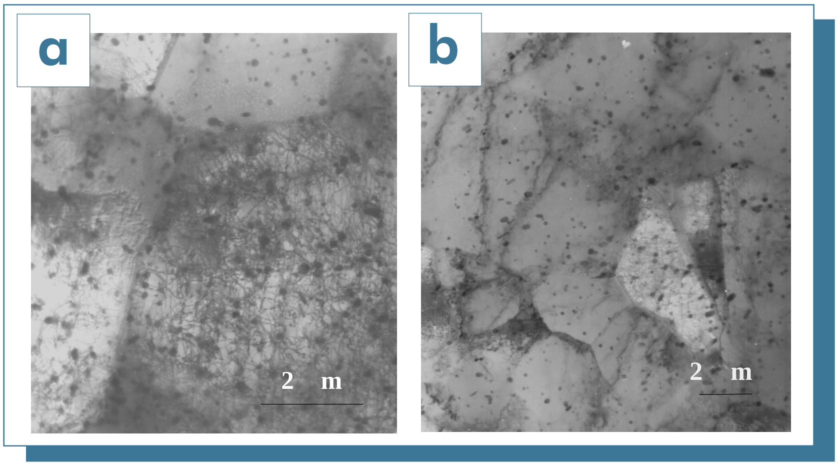

Fig. 7: Microstructure of the joint (TEM): a) transition between recrystallized and non-recrystallized zones; the pinning effect of precipitates is apparent; b) typical morphology of recrystallized grains; the fine grain size and the relatively high fraction of precipitates can be easily appreciated

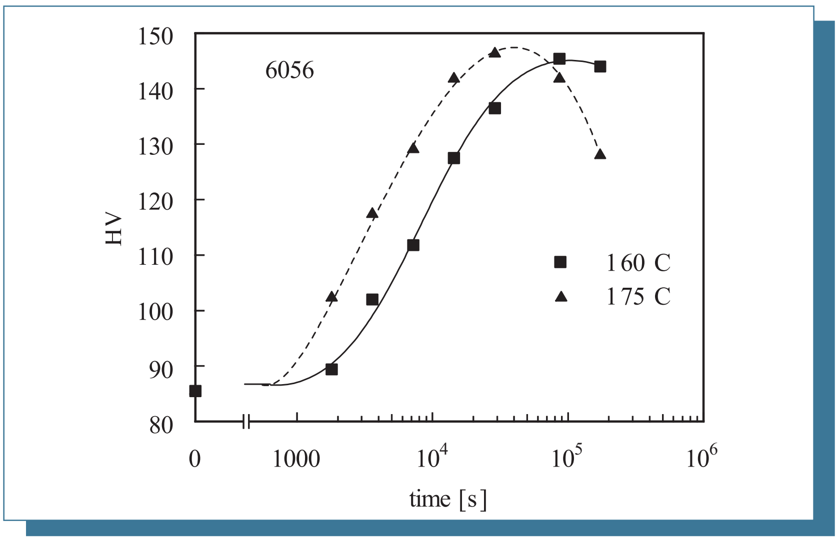

Fig. 8: Ageing curves obtained on parent alloy after solution treatment at 530°C for 4h

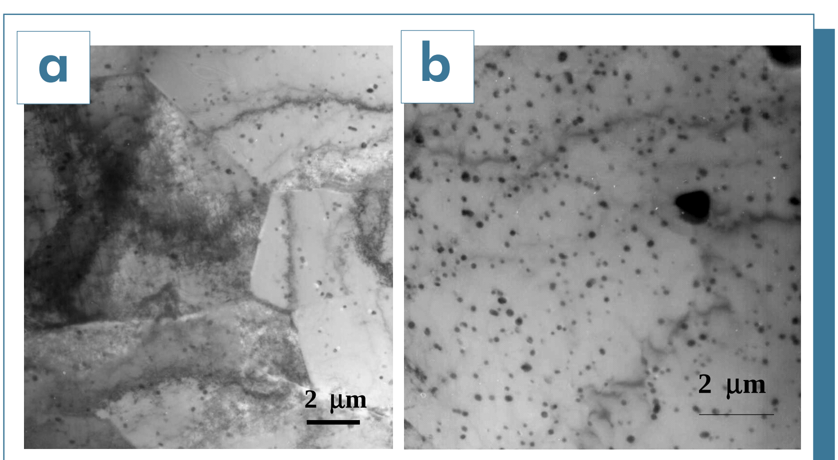

Fig. 9: Microstructure of weld-nugget after T6 treatment (TEM); a) effect of grain growth during solution treatment; b) distribution of precipitated Mg_2Si

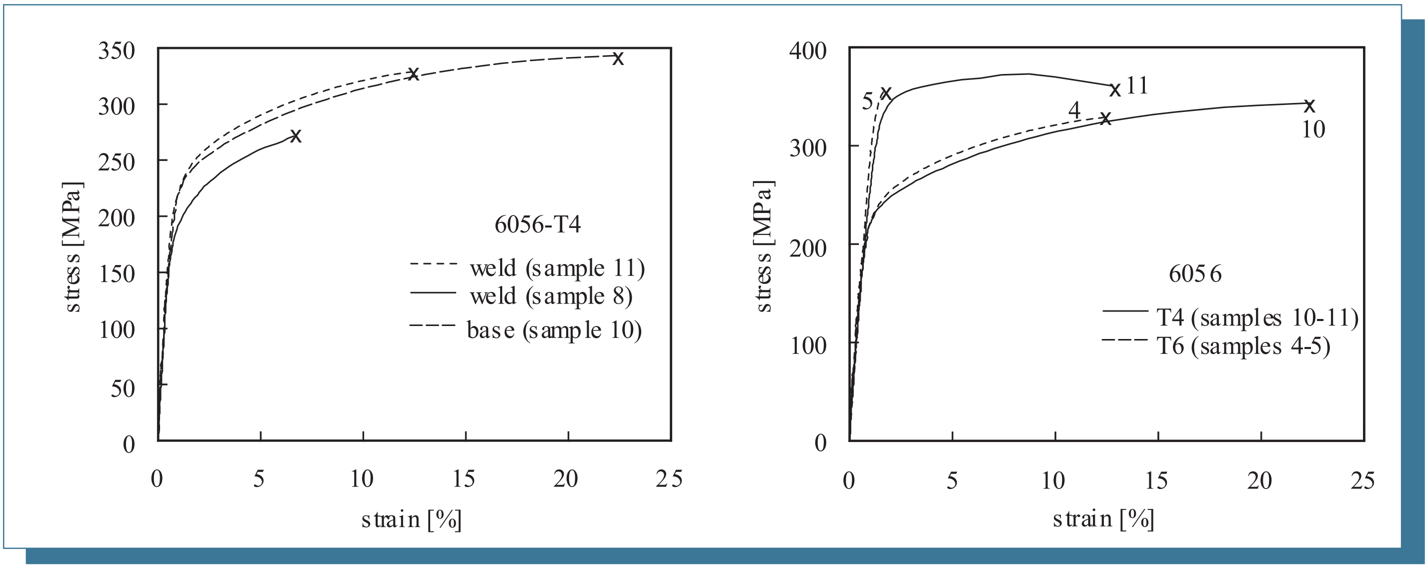

Fig. 10: Stress-strain curves for weld and parent material

CONCLUSIONS

FSW was found to produce microstructural variations across the weld, due to the thermomechanical treatment involved in the process. Such variations result in local changes in mechanical properties. Nevertheless, the tensile strength of the welded joint is close to 90%, and its yield strength is almost equivalent to those of the parent alloy, an extremely satisfactory result that demonstrates the high quality of the process. After a T6 heat treatment, tensile strength rises to 95% of that of the parent alloy. The only disadvantage with FSW welding is a reduction of the material ductility, a disadvantage is enhanced bt subsequent T6 treatment.

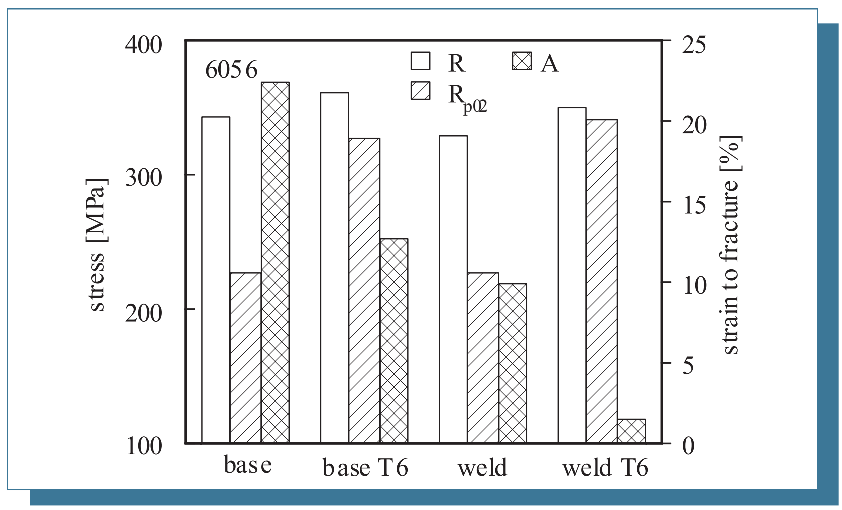

Fig. 11: Histogram showing the mechanical response (rupture strength, R, yield strength, R_{p02}, and ductility, A) for the FSW material; samples 4 and 10 were used to estimate the properties of base material, and samples 5,6,11 and 12 for the weld

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