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On the fatigue behavior of friction stir welded AlSi 10 Mg alloy

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Abstract

The high cycle fatigue behavior of friction stir welded AlSi10Mg samples was investigated for a stress ratio R = 0.1, ranging from 0.5 to 0.9 of the yield strength, in addition to tensile tests. The welds were produced with different tool rotation and travel speeds, and these welding parameters were correlated to residual stresses, measured by X-Ray diffraction (sen^2 Ψ method). Moreover, the residual stresses were measured during the fatigue testing, at fixed cycle intervals, being reported. It was observed that the residual (compressive) stresses within the nugget were smaller than in the interface regions (between the thermo-mechanically affected zone and the base metal) and stabilized above 4×10^5 cycles. Fatigue crack morphology and microstructural changes were characterized by optical and electron microscopy and the observations are discussed along with the fatigue results.

Keywords

Friction stir welding. Fatigue properties. Residual stresses. Aluminium alloys.

Comportamiento a la fatiga de soldaduras por fricción lineal de AlSi 10 Mg

Resumen

Se estudia el comportamiento a la fatiga de alto ciclo de muestras de AlSi10Mg soldadas por fricción lineal para relación de tensión R = 0,1 cubriendo el rango de 0,5 a 0,9 de la resistencia a tracción, además de los datos del ensayo de tracción. Las soldaduras ensayadas fueron producidas con diferentes velocidades de rotación y avance de la herramienta. Las variables de proceso han sido correlacionadas con el análisis de tensiones residuales por difracción de Rayos X (método sen^2 Ψ). Además, se midieron las tensiones residuales durante la deformación en fatiga a intervalos regulares de ciclos. Se observa que las tensiones residuales (de compresión) dentro del nugget son más reducidas que en la interfase entre la región afectada térmica y mecánicamente y el material base, y se mantuvieron estables de manera progresiva a partir de los 4×10^5 ciclos. Se ha empleado la microscopía óptica y de barrido para evaluar la morfología y microestructura de las grietas de fatiga. Estos resultados se analizan conjuntamente con los ensayos mecánicos.

Palabras clave

Soldadura por fricción lineal. Propiedades de fatiga. Tensiones residuales. Aleaciones de aluminio.

1. INTRODUCTION

In the early 90's, The Welding Institute (TWI) in the U.K. presented a novel welding method based upon friction- Friction Stir Welding (FSW)- in which a shouldered spinning cylindrical tool with a profiled probe is forced into the abutting edges of the parts to be joined, as suggested in figure 1. The pressure and rotational motion generate frictional heat, producing a weld joint by plastic mixing of the (identical or dissimilar) workpiece materials. It is a solid state joining process, operating bellow the melting point of the materials, with no shielding gas or any welding consumables required. Currently applied in production of mainly automotive manufactures[2 and 3] railway[4] and shipbuilding or marine industries[5], the process is used for alloys that cannot be joined by conventional fusion techniques. The ongoing development of the FSW tools has, in the meanwhile, allowed a wide range of materials to be successfully produced: aluminium alloys, copper, titanium and magnesium alloys, zinc, mild steels, composites and plastics[6-10].

The ability to model the overall process and further predict the industrial production of welds in a wider range of materials, is based upon

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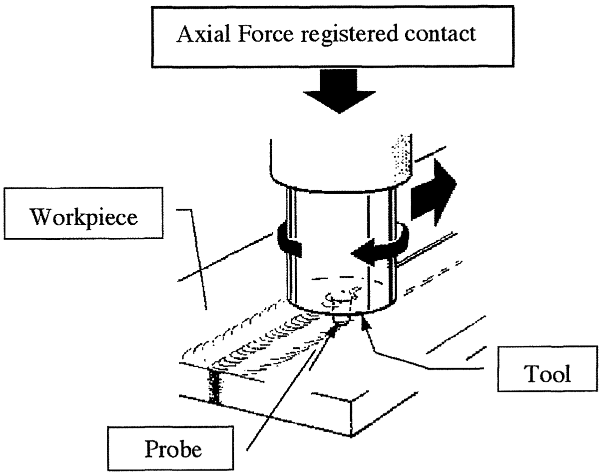

Figure 1. Schematic illustration of the friction stir welding principle.

Figura 1. Esquema general del proceso de soldadura por fricción lineal.

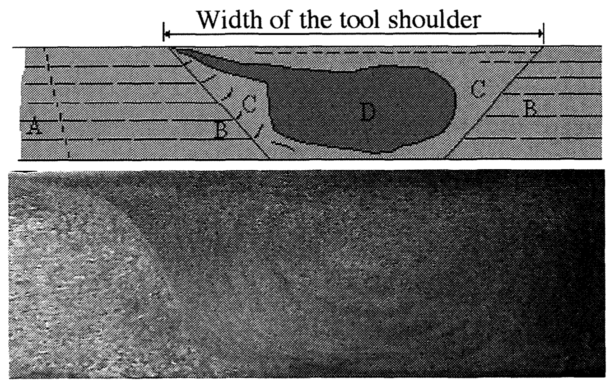

Figure 3. Schematic (adapted from[11]) and macrograph of the relevant microstructural features in a friction stir weld A- Base material; B – Thermally afected zone; C - Thermomecahnically affected zone; D – Dynamically recristalized.

Figura 3. Esquema (adaptado de [11]) y macrografía de la microestructura típica de una soldadura por fricción lineal A-material base, B- región afectada térmicamente, C- región afectada térmomecánicamente y D- región recristalizada dinámicamente.

understanding how the material flows, in particular how is deposited behind the probe (pin). This is currently under investigation[9].

In general, a coarse screw thread is needed for the pin´s surface, promoting the motion of material around the pin, and hence, a porosity or void free weld[11]. The stirring effect is portrayed in figure 2. The material is transferred from the leading edge to the trailing edge of the pin, leaving a solid joint between the pieces. The macrostructure and schematic depicted in figure 3 illustrates the well-defined features of the joint, in particular the dramatic variation in microstructure from within the welded zone (small, relative equiaxed grains) to large elongated grains zones, away from the weld. The crushing, stirring and forging action of the tool produces a remarkable nugget with a finer (dynamically recrystallized) microstructure than the parent material, the form of which can vary according to the type of alloy and process conditions. In thermomechanically-affected zone, C in figure 3, the material has been subjected to plastic deformation and thermal effects from the joint, usually bending the elongated grains in an onion-like arrangement. Zone B material remains undeformed, in what is simply a thermally affected zone, typically overaged area, making the transition to the parent material, A. It should be pointed out that a limited amount of deformation occurs below the pin, and even then very close to its surface.

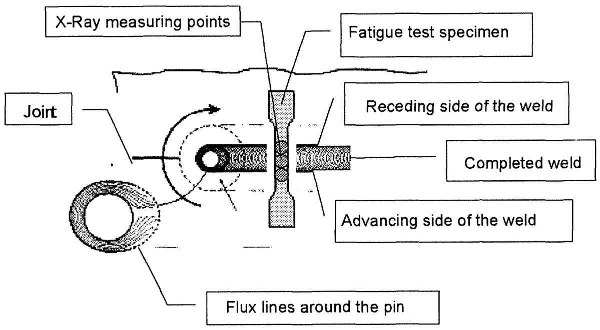

Figure 2. Representation of the stirring and forging action of the FSW tool (top view), fatigue test specimen and X-ray measuring points, 1, 2 and 3 from the advancing to the receding side of the weld.

Figura 2. Representación de la acción de mezcla y forja de la herramienta de soldadura por fricción lineal (vista superior); probeta de fatiga y puntos de medida de difracción de rayos X, 1,2,3.

Most of the work published to date, besides dealing with the parameter optimization of the process, in particular tool rotation speed and tool advancing speed, has reported on the mechanical and metallurgical properties that can be obtained[11]. However, the effect of such parameters, including the tool geometry, on weld quality and performance is still poorly understood[9]. In general, the good mechanical properties and low distortion of the pieces, with low residual stress levels related to microstructural features and attributed to the low heat input during processing, have been described in isolated reports.

For most of practical applications, fatigue strength becomes paramount in the components performance. Components behaviour under cyclic loading, is known to be influenced by the materials properties and microstructure and the magnitude and distribution of residual stresses, as the joints consist of very distinct zones with considerably diverse properties such as hardness, strength, ductility, or even local chemical composition.

It has been reported that FSW is used to join lightweight AlSi10 Mg alloys without altering the chemical composition and less degradation of strength than is usual in conventionally fusion-welded aluminiums[9]. Studies on tensile properties of FSW 6XXX and 7XXX series alloys showed that post weld heat treatment could bring the tensile strength to that of the parent material, at moderate expenses from ductility[2]. Zhang *et al.* [12] results on 7010-T7651 welded to 7010-T7651 showed that the fatigue life (~10Hz, R=0.1) of the friction stir welded structure considerably approach that of the parent material structure, even though a wide scatter is associated to both. Fatigue cracks are reported to initiate from a region 2 mm to 8.5 mm away from the weld centerline, on the datum face of the specimen; hence, the specimen geometry outdoes the small effect of residual stresses[12 and 13].

James *et al.* [14] examined residual stresses in aluminum alloys after FSW. Results showed that within the recrystallised region residual stresses are zero, moderate stresses being present in the partially recrystallised and thermomechanically affected zone. These stresses are considerably below those created by fusion welding processes.

In the same way, results on fatigue tests on FSW of 5083 and 2014 aluminium alloys were reported to be exceptional as far as the little scatter and the improvement form conventional TIG and MIG processes are concerned, considerably exceeding BS 8118 class 35 and the European design recommendation ECCS B3 for fusion welds. When tested using a stress ratio of R = 0.1, the fatigue performance was comparable to that of the parent material.

In this paper we present preliminary results on the high cycle fatigue behavior of friction stir welded AlSi10 Mg alloy (6082) in the T6 condition (solution heat treated and artificially aged), relating the welding parameters to final mechanical properties. Furthermore, we report the evolution of the magnitude and distribution of residual stresses during the fatigue testing, measured by X-Ray diffraction at fixed cycle intervals.

2. EXPERIMENTAL PROCEDURE

The testing material consisted of eight plates with approximate dimensions, 140 × 220 × 4 mm^3, of AlSi10 Mg alloy. These plates were butt welded by FSW at Daimler Chrysler AG, using the parameters showed in table I.

Each welded plate was sectioned perpendicular to the weld seam to prepare specimens for metallographic observation. These specimens were mechanically polished down to diamond paste 1 μm and then etched with Keller or Poultons based solutions. Etching of these alloys is particularly difficult and several alternate operations of polishing and etching were required to reveal the structure of the nugget (Fig. 4).

Specimens for mechanical testing, both tensile and fatigue, were prepared by water jet cutting to prevent, as much as possible, further changes to the residual stress fields in the specimens. These specimens were removed in the perpendicular direction to the weld seam (as suggested in Figure 2 inset). The gauge length of all specimens was then polished to remove machining irregularities. Additionally specimens of the base material were also manufactured for comparison purposes, following the same procedure.

Tensile tests were performed in an electromechanical universal testing machine, according to EN10002. Due to the limited amount of welded material only one test for each welding condition was performed. Tensile tests were not performed in the base material as all the welded specimens failed by this material. Fatigue tests were performed at room temperature in a servohydraulic testing machine under load control. A range of stresses within the elastic regime of the material (varying from 50 to 90 % of the yield stress

Table I. Summary of welding parameters used for production of testing samples

Tabla I. Parámetros de soldadura empleados en la producción de las probetas ensayadas

Plate ID	Welding Parameters: Tool Rotation Speed [rpm]	Welding Parameters: Tool Travel Speed [mm/min]
A1	1120	500
A2	1400	300
A3	1400	700
A4	710	300

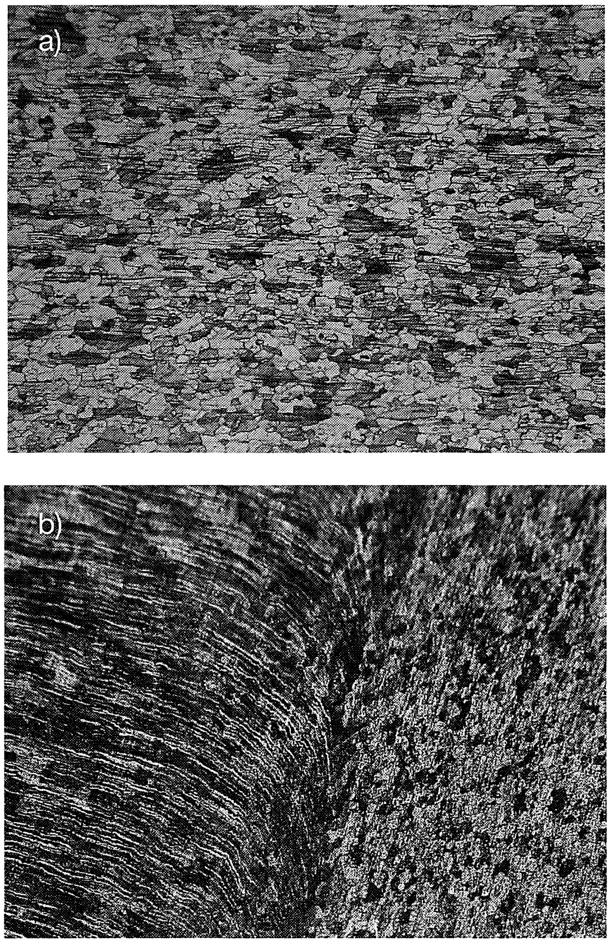

Figure 4. Micostructures of typical: a) base material, b) weld nugget and transition zone.

Figura 4. Microestrucuturas típicas de: a) material base, b) botón de la soldadura y zona de transición.

determined in the tensile tests) was used for each welding condition. All fatigue tests were performed at a frequency of 20 Hz and a stress ratio R = 0.1.

Fatigue specimens from plates A1, A2 and A4 (Table I), tested at 60 % of the yield stress, were selected for residual stress measurements during fatigue. In each specimen three measurement points were selected, one in the welding nugget and two in the thermomecahnically affected zone both on the advancing and receding side of the weld, respectively (see inset in Figure 2). Prior to the residual stress measurements, the pre-defined measuring points were electrolytically polished, in order to remove residual stresses introduced by the mechanical polishing of the specimens. Special care was taken during this later polishing in order to remove just a few microns of the surface, preventing notches that could affect the fatigue performance. Residual stress measurements were performed by X-ray diffraction, using the $\sin^2\psi$ method. This method consists of the determination of 2θ angles (θ is the Bragg angle) for a set of ψ incident angles. Residual stress values were directly proportional to the slope of the linear fit of 2θ angles against $\sin^2\psi$. All the measurements were performed with a RIGAKU Strainflex MSF-2M system. Residual stress measurements were performed in each selected fatigue specimen, at the three pre-defined points prior fatigue testing in order to establish the initial stress level. Fatigue tests were then interrupted at 10^5, 2×10^5, 3×10^5, 5×10^5, 10^6, 1.5×10^6, 2×10^6, 2.5×10^6 and 3×10^6 cycles when further measurements were performed, allowing the evolution of residual stresses with the mechanical cycling to be monitored. Fatigue tests were then resumed up to specimen failure or a life of at least 10^7 cycles was achieved. Fatigue testing was completed with additional specimens, width no interruption for residual stress measurements.

3. RESULTS AND DISCUSSION

Welds were fabricated by FSW using different process variables (Table I). Distinctive structures, unattainable by conventional welding techniques were developed. A typical macrostructure of the welded joint (Fig. 3) depicts a weld nugget surrounded by a thermomechanically affected zone (TMZ). A thorough examination of several cross sections removed from different parts of the welds did not reveal any inclusions or pores within either the nugget or the TMZ. The microstructure of the alloy, shown in figure 4a) depicting elongated grains from rolling, changes to a finer

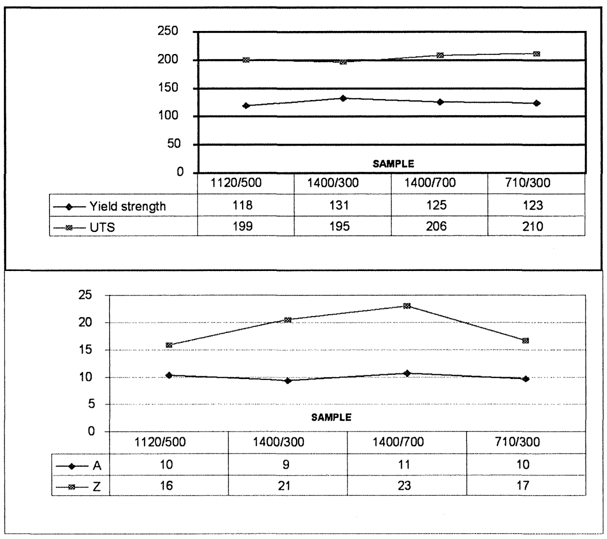

Figure 5. Summary of tensile properties.

Figura 5. Resumen de las propiedades de tracción.

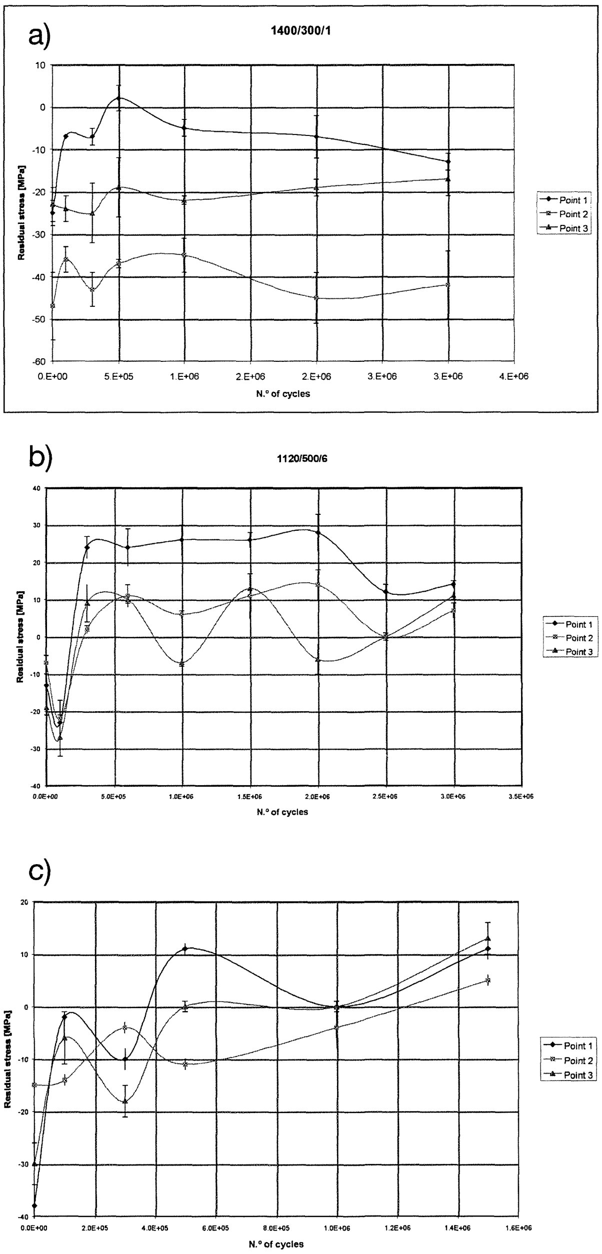

Figure 6. Variation of residual stresses with cyclic loading in specimens (a)1400/300. (b) 1120/500, and (c) 710/300, respectively.

Figura 6. Variación de las tensiones residuales con los ciclos de fatiga de las probetas (a)1400/300 (b) 1120/500, y (c) 710/300.

microstructure within the TMZ and the nugget. The latter exhibits a distinctive banded, onion ring structure. An example of the microstructure from the TMZ at the nugget boundary is presented in Figure 4b). In this region the welding causes bending of the elongated grains. Evidence of dynamic recrystalization arising from shear instabilities (localized high rate deformation), like those referred in[11], is observed. In the adjacent region, the undeformed zone (B in Fig. 3), properties remain influenced by the heat from the weld. Examination of hardness (not shown) reveals a minimum in this region, which must result from an overaging or annealing process[11]. Further research, regarding the precipitate nature and distribution within this region, where recrystallization seems apparent, is underway.

The FSW was shown to produce sound welds with very little tensile strength scatter between welding conditions. Tensile strength was shown to be around 200 MPa and yield stress close to 125 MPa, on average. These values are eventually on the low end of the scatter band for this material, but it should be noted that, in all tested specimens, failure occurred in the base material.

The evolution of residual stresses with mechanical fatigue cycling, presented in Figure (a-c), did not show much variation between the different welding conditions. The residual stresses determined in the specimens, while considerably low compared to those typical from conventional fusion processes, were smaller than those from the as-welded condition (not shown). In the as-welded plates, tensile residual stresses were found at the center of the seam (nugget). This remains the most stable area throughout testing (central point in figure 3). In all tested specimens, the residual stresses in the receding side of the seam (lower point in figure 3) are always lower than those in the advancing side of the weld. It also seems that the main residual stress variations occur below 5×10^5 cycles, after which the behavior of the curves tends to stabilize uniformly within the gauge length of the specimens.

The fatigue tests were pursued in other specimens, without interruption for residual stress measurements, until rupture or to a point where a considerable number of cycles were achieved, as in the case of the base material. Figure 7 gives the results of the initial fatigue data produced. The fatigue data of the FSW samples fall in a same scatterband, irrespective of the different processing parameters used for welding. Moreover, it reaches but a fraction of the fatigue strength of the base material, in accordance to what was previously reported[13].

Fractographic analysis, using SEM, showed that crack initiation occurred always outside the nugget, in the border between the thermomechanically affected zone and the base material (Figs. 8a and b). The residual stresses developed during fatigue seem to have a limited

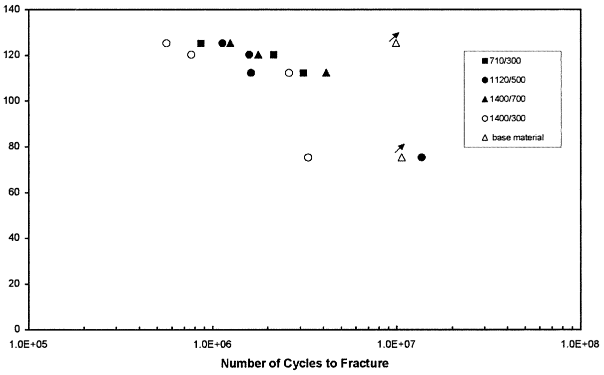

Figure 7. Plot of the fatigue test results.

Figura 7. Resumen de los resultados de ensayos de fatiga.

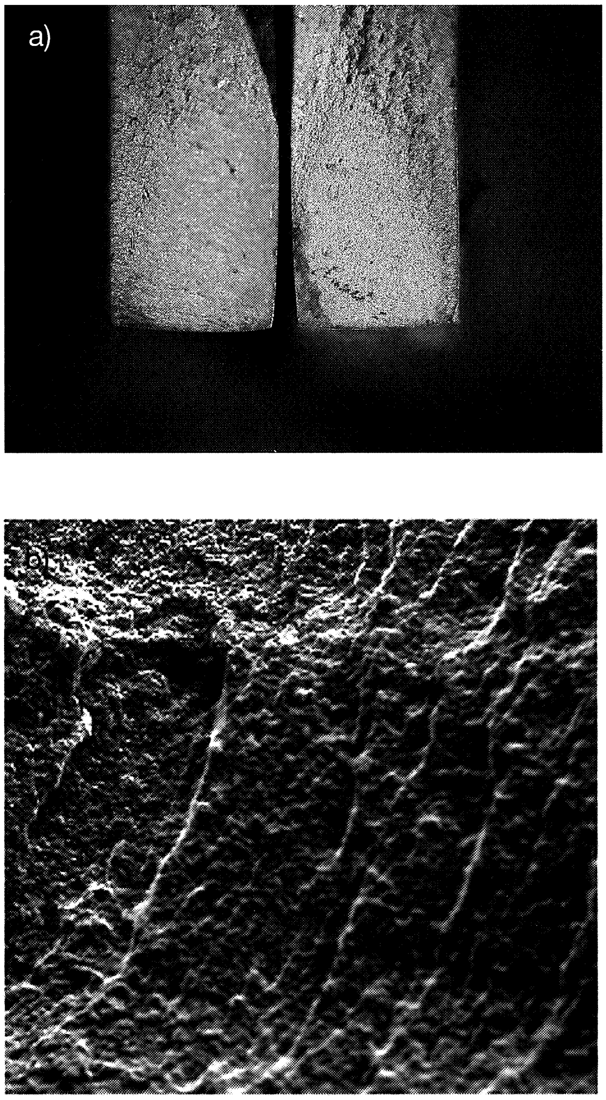

Figure 8. Fracture surface of (a) 1400/300 weld tested at 75 MPa (20x) and (b) crack propagation region with beach marks (200x).

Figura 8. Superficie de la grieta (a) del material soldado 1400/300 ensayado a 75 MPa y (b) de la región de propagación visible de las marcas de playa (200x).

effect on the fracture initiation; which is in accordance to what has been previously reported by Zhang *et al.* [12]. A justification can be found in the microstructural evolution of this thermally affected zone, in what concerns reprecipitation during cooling from the friction stir welding operation and is currently under investigation.

4. CONCLUSIONS

The FSW process can produce, under different processing parameters, sound welds with low levels of residual stresses and defects. Residual stresses developed during fatigue cycling were measured at fixed intervals and appear to have a limited contribution to failure. Fatigue strength of the FSW specimens reached only a fraction of the fatigue strength of the base material. Cracks nucleated outside the nugget, in the border between the thermomechanically affected zone and the base material, giving relevance to the microstructural developments during cooling from welding.

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