Mechanical Behaviour of friction stir butt welded joints under different loading and temperatures conditions

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Abstract

Friction Stir Welding is a process that has led to an increase in the use of aluminum and its alloys in different industries, since, as an autogenous, solid-state welding process, it allows to obtain significantly lighter structures that benefit from the absence of melting of the base materials.

The work developed within the scope of this thesis was focused on the analysis of the mechanical behavior of AA7075-T651 friction stir butt welded joints, of 4 mm in thickness, under different loading and temperature conditions. A selection process was put into place in order to assure that appropriate welding parameters were being used to produce the welds from which fatigue specimens would be manufactured from. The welds from which those specimens were manufactured from were submitted to non-destructive tests in order to assess the presence of welding defects.

Fatigue tests were carried out, under a constant amplitude loading regime, at two different stress ratios (0.05 and 0.5) and two different temperatures: 23 ºC and 150 ºC.

The results obtained by the fatigue tests point out to a higher fatigue life of the specimens when the highest stress ratio, R= 0.5, was employed (for the maximum stress applied), for both loading temperatures. For the stress range, the contrary was found to be true: the lower stress ratio resulted in a higher fatigue life of the specimens. Room temperature was also found to result in a significantly better fatigue performance.

A Scanning Electron Microscope was used in order to characterize the fatigue fracture surfaces.

Keywords

Friction Stir Welding; Fatigue; Stress Ratio; Temperature; AA7075-T651.

1. Introduction

Aluminum and its alloys have seen their applications in multiple industries increase over the last years as a result of the emergence and development of a joining process that allows to obtain aluminum welds with excellent mechanical properties: Friction Stir Welding (FSW). FSW is a solid-state welding process during which melting of the base material does not occur which allows aluminum alloys that were thought to be not weldable to be welded. As for its working principle, a non-consumable, rotating, hardened steel tool, with a cylindrical shape constituted by a pin and a shoulder, is driven into the weld joint until the pin has completely penetrated the joint and the shoulder is in contact with the surface of the workpieces. Then, the tool is traversed along the joint line, at a constant transverse speed (welding/travel speed). The rotating tool generates enough heat (by interfacial and internal friction dissipation) and plastic deformation to weld the workpieces together (the tool is responsible for mechanically mixing and joining the workpieces). As the tool moves along the weld line, the material is stirred by the pin being moved from the front of the tool into the trailing edge, where it is posteriorly forged, and the weld is then obtained. Additionally, since it is an autogenous welding process, no filler material is required in order to achieve the joining of the materials thus, it is possible to obtain lighter structural parts, which is of special interest for the aerospace and automotive industries.

The majority of structural parts must undergo dynamic loads (loads that vary with time) therefore, fatigue failure is of major interest as it is the most probable failure mechanism. In fact, fracture induced by fatigue is the principal cause of failure in joints obtained by means of FSW [1]. The loading temperature and stress ratio (R) are some of the factors that influence the fatigue crack growth rate and consequently play an important role in their fatigue performance.

There are several researchers who have studied and evaluated the effect of these parameters over the fatigue life of welds obtained by FSW. Some examples are presented next.

Resan et al [2] found that the fatigue life of welds obtained by FSW decreased with an increase in the temperature at which the fatigue tests were being performed. The research consisted in the investigation of the effect of both the loading temperature and tool rotational speed over the fatigue life of AA2024 friction stir welds. It was concluded that for the same tool rotational speed, increasing the fatigue testing temperature had a detrimental effect over the fatigue life of the welds.

By their turn, Tra et al [3] witnessed that the fatigue crack growth rates were sensible/influenced by the temperature at which the fatigue tests were carried out. A comparison was made between the rates obtained at room temperature and at 200 ºC. The results point out to the same conclusion obtained by Resan et al [2]. These experiments were performed in AA6063-T5 FS welded joints.

Li [4] observed the effect of different stress ratios over the fatigue crack growth rate of AA7075-T651 friction stir welds. Li [4] was able to conclude that higher stress ratios have a more detrimental effect over the fatigue life of the welds since higher stress ratios led to higher fatigue crack growth rates. From the experimental work that was developed it was also possible to see that this effect becomes less significant as the stress ratio value increases.

No work regarding both the effect of the loading temperature and stress ratio over the number of cycles until failure of this type of welds occurs was found in the available literature.

2. Material and Methods

2.1. Base Material Characterization

AA7075 rolled plates with a thickness of 4 mm, in the T651 condition, were used as base material.

Their chemical composition was determined by an EDS (Energy Dispersive Spectroscopy). Three alloying elements were identified: Magnesium (Mg), Copper (Cu) and Zinc (Zn), with the main alloying element being Zinc, as expected, considering that it is an alloy from the 7XXX series [10]. In Table 1, some of the AA7075-T651 mechanical properties are listed.

Table 1- AA7075-T651 Mechanical Properties [10], [11].

Mechanical Property	Value (Units)
Yield Strength	503 (MPa)
Ultimate Tensile Strength (UTS)	572 (MPa)
Poisson's Ratio	0.33
Modulus of Elasticity	72 (GPa)
Vickers Hardness	193 (HV2.0)

2.2. FSW Production

All the friction stir welded joints produced within the scope of the thesis, were performed on an ESAB LEGIOTM FSW 3UL® numeric control machine.

The machine contains a welding head capable of moving along the x, y and z axis. In the production of the welds, a clockwise rotational speed was selected. The third version of the tool developed by Vilaça et al. [5], at IST, designated iSTIRtool_v3, was used. The tool is composed by 3 distinct parts: the tool body (responsible for supporting the mechanical stresses involved in the welding process and dissipating the resulting heat that is generated), the shoulder and the pin. The pin for this work had a conic shape.

As previously mentioned, the main goal of the experimental work that was developed was to assess the mechanical behavior of friction stir butt welded joints, under different loading and temperatures conditions. A selection process that would allow to select an appropriate set of welding parameters was put into place. It was divided in which was divided in 3 phases: Visual Inspection, Preliminary Non-Destructive Testing and Preliminary Uniaxial Quasi-Static Tensile Testing.

The welding parameters found to be appropriate are listed in Table 2 and were used to produce a weld designated L1. Different welds were posteriorly produced resorting to those welding parameters (those welds are designated as L2, L3, L4, L5, L6 L7 and L8).

Table 2- Welding parameters used to produce the L1, L2, L3, L4, L5, L6, L7 and L8 welds.

Process Parameter	Value (Units)
Initial Welding Position	0.8 (mm)
Tool Force	950 (kgf)
Tool Rotational Speed	1000 (rev/min)
Plunge Speed	0.1 (mm/s)
Dwell Time	4 (s)
Welding Speed	8 (cm/min)
Tilt Angle	1.5 (°)

2.3. Non-Destructive Testing

Welds were taken to the Non-Destructive Testing Laboratory, located at the Nova School of Science and Technology, where they were submitted to non-destructive tests to assess the existence of welding defects. As for the specific non-destructive inspection method, Eddy Current Testing was selected as it was suitable considering the material used in the experimental work: an aluminum alloy.

Regarding the equipment, a probe, operating at 1.1 MHz, 6º with a gain of 70 dB combined with a NORTEC 500C impedance analyzer, were used in the tests.

2.4. Metallographic Analysis of the Welds

Two different types of metallographic analysis were conducted: a macrographic and a micrographic analysis. Two samples were cut out from 2 different welds, transversally to the welding direction: one from the L1 weld and one from the D13 weld, for which during the execution of the preliminary non-destructive tests a welding defect was detected.

The main goal was to study the impact caused by this welding defect over the hardness profile of the welds. The samples were posteriorly placed into epoxy resin, sanded, polished and etched by using Keller's reagent that had the following chemical composition: HNO_3 (2.5 mL), HCl (1.5 mL), HF (1 mL) and H_2O (95 mL).

2.5. Hardness Testing

In order to depict the mechanical and structural properties of the welded joints, Vickers hardness tests were performed. For each one of the aforementioned samples, indentations were made along 3 different straight lines: at 0.5 mm from the top surface of the weld, at the mid-thickness of the samples and at 3.5 mm from the top surface of the weld, with a load of 2 kgf and an indentation time of 10 seconds. All the hardness tests were performed in a Mitutoyo Hardness Tester (model AVK-C2). Regarding the spacing between each indentation, from the weld center up to 2.5 mm, on both sides, the interval was set to 0.5 mm. From there, to the edge of the samples, the space between each indentation was set to 1 mm.

2.6. Uniaxial quasi-static Testing

Uniaxial quasi-static tensile tests were performed in order to assess the tensile properties of the welded joints. The tensile specimens were manufactured from the welded plates, transversally to the welding direction. The uniaxial quasi-static tensile tests were carried out at room temperature with a displacement rate speed of 5 mm/min. The equipment used for this purpose was a Instron 3369, with a load cell of 50 kN.

2.7. Fatigue Testing

Fatigue Testing was carried out on a servo hydraulic Instron machine (model P8502) equipped with a load cell of 10 kN. The tests were performed at two different temperatures: room temperature and 150 ºC. For those tests an Instron furnace equipped with a temperature controller was used in order to control the testing temperature and to ensure that the fatigue tests were performed, entirely, at the desired temperature. The specimens used for these tests were in all aspects equals to the ones used in the uniaxial quasi-static tensile tests. All the fatigue tests were carried out until the fatigue specimens fractured or until the run-out limit (established at $2x10^6$ cycles) was attained. The fatigue tests were executed under 2 stress ratios (0.5 and 0.05) and loading temperatures (23 and 150 ºC).

3. Results & Discussion

3.1. Metallographic Analysis of the Welds

The macrograph and micrographs obtained for the D13 and L1 samples are shown in Figures 1 and 2, respectively. Through the analysis of the macro and micrographs obtained for both samples, it was possible to identify all the typical microstructural regions of welds obtained by FSW: SZ, TMAZ, HAZ and base material.

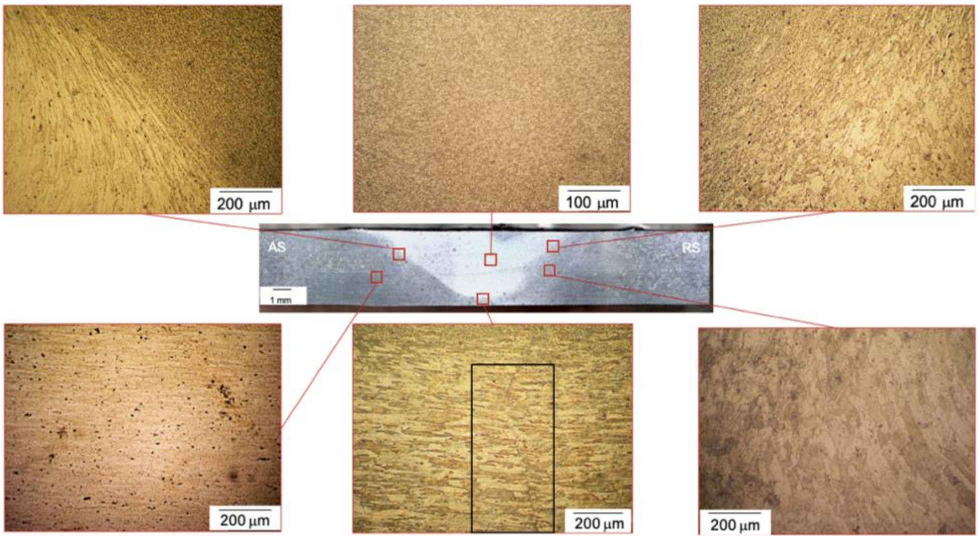

Figure 1- Macrograph and micrographs obtained for the D13 sample.

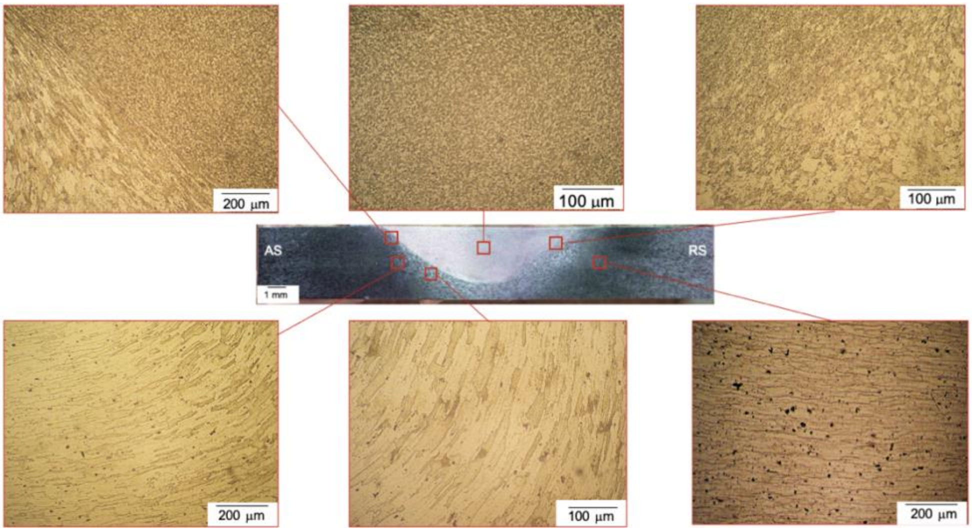

Figure 2- Macrograph and micrographs obtained for the L1 sample.

The SZ appears in the center of the macrographs in a clearer color tone (whitish). In this region, in both samples, a fine, homogeneous, equiaxed microstructure can be encountered as a result of the dynamic recrystallization that the material undergoes. The L1 sample has a lower grain size in the SZ, comparatively to the one presented by the D13 weld in the same region. This observation can be explained by the different heat inputs that were used in order to produce the welds.

Regarding the TMAZ, it can be identified as being the closest region to the stir zone, with a slightly darker color tone and a different grain morphology. When observing the micrographs corresponding to the TMAZ, it is possible to identify the highly deformed grain structure that characterizes this region. This highly deformed microstructure is more evident in the interface between the TMAZ and the SZ. Another important aspect worth mentioning is that the micrographs also allow to verify that the transition between the TMAZ and the SZ is smoother and harder to detect at the retreating side of the weld.

As for the HAZ, it can be identified as being the region with a darker color tone and different grain morphology comparatively to the one presented by the TMAZ. Regarding its microstructure, the grain size is higher when compared to the one found in the aforementioned regions and more strengthening precipitates are encountered.

The welding defect detected during the execution of the non-destructive tests is highlighted in black in Figure 1. Regarding its classification, it is a root defect of the Kissing Bond type with visible traces of the two original aluminum plates that were used to obtain the D13 weld.

3.2. Hardness Testing

Vickers hardness tests were carried out in the L1 and D13 samples at 0.5, 2 and 3.5 mm from the upper surface of the welds. The hardness profiles obtained at 3.5 mm from the top surface of the L1 and D13 sample are shown in Figure 3.

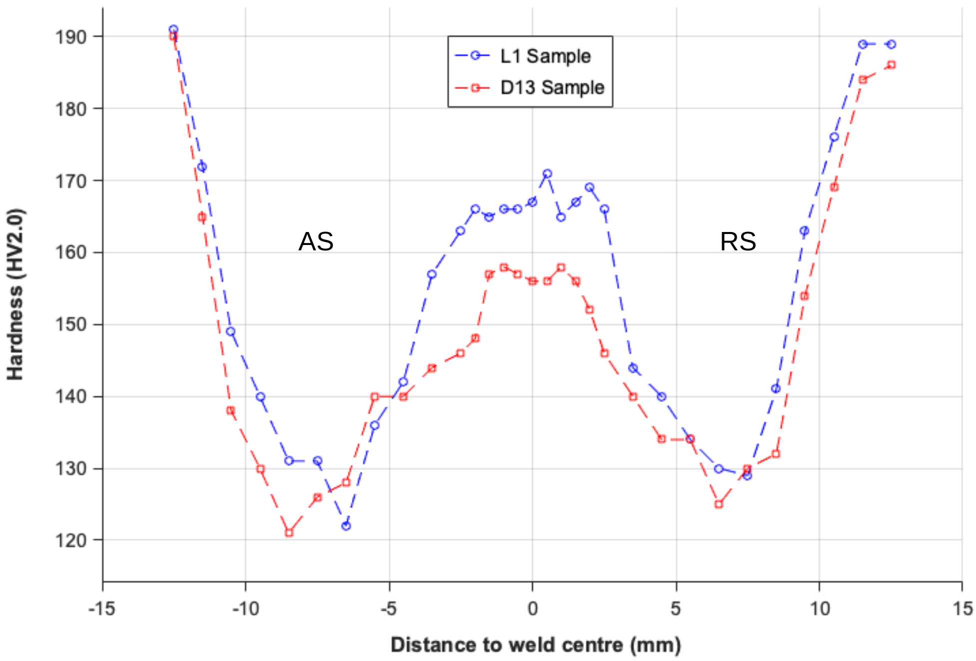

Figure 3- Hardness profiles at 3.5 mm from the top surface of the L1 and D13 samples.

Through the analysis of the results that were obtained, it is possible to identify a plateau surrounding the weld center, which extents up to approximately 4 mm, on both sides, where the hardness remains approximately constant. This hardness uniformity is a result of the homogeneous microstructure found in the stir zone, which has been discussed previously.

For both samples, the hardness values decrease progressively along the TMAZ (as the distance to the weld center increases) with the absolute minimum hardness values being registered, primarily, in the advancing side of the weld and more specifically, at the interface between the HAZ and the TMAZ (for both sides of the weld, the lowest hardness values are found at this interface). Similar results were obtained by Balasubramanian et al. [6].

According to Pankade et al. [7], who analyzed the hardness profile obtained for AA7075-T6 friction stir welds and obtained identical results, such an observation can be explained by the precipitate overaging and consequent coarsening that occurs in this region, as a result of the thermal cycle that the material undergoes.

Along the HAZ of both welds, the increase in distance to the weld centre is accompanied by a hardness increase since, gradually, lower temperatures and cooling rates are attained as the distance to the base material decreases. The values registered for the D13 sample are, generally, lower, especially in the stir zone, comparatively to the ones obtained for the L1 sample. Such trend can be explained by the lower grain size found at this region in the L1 sample.

The effect of the Kissing Bond defect that was detected in the D13 sample was not noticeable, since there was no significant and punctual drop in the hardness profile of the D13 sample, in that region, as it can be noticed by analyzing Figure 3.

3.3. Uniaxial Quasi-Static Testing

The Load-Displacement curves obtained for each tested specimen are shown in Figure 4.

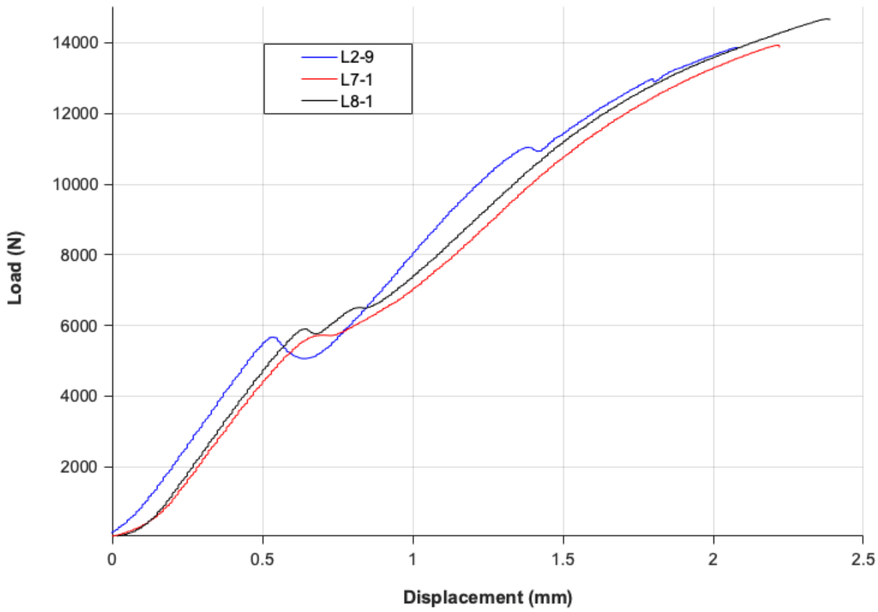

Figure 4- Load-Displacement curves obtained for the L2-9, L7-1 and L8-1 specimens.

The three tested specimens possess the same yield strength, around 305 MPa. Comparatively to the base material, which has a yield strength of 503 MPa, as listed in Table 1, this value corresponds to a decrease of approximately 39%. The ultimate tensile strength (UTS) registered was very similar with an average of 360 MPa and a standard deviation of 11.3 MPa. Such a value corresponds to a joint efficiency of approximately 63%. Both observations (regarding the yield and UTS of the specimens) are in accordance with the work developed by several authors: Balasubramanian et al. [6], Çevik et al. [8] and Linton & Ripley [9], who obtained similar results in tensile tests carried out in AA7075-T651 specimens obtained from friction stir welds.

3.4. Fatigue Testing

The results obtained through the execution of the fatigue tests at 23 ºC and 150 ºC are presented in the form of S-N curves, for the maximum stress applied, in Figures 5 and 6. Regarding the S-N curves obtained taking into account the stress range applied during the tests carried out at 23 ºC and 150 ºC, they can be found in Figures 7 and 8, respectively.

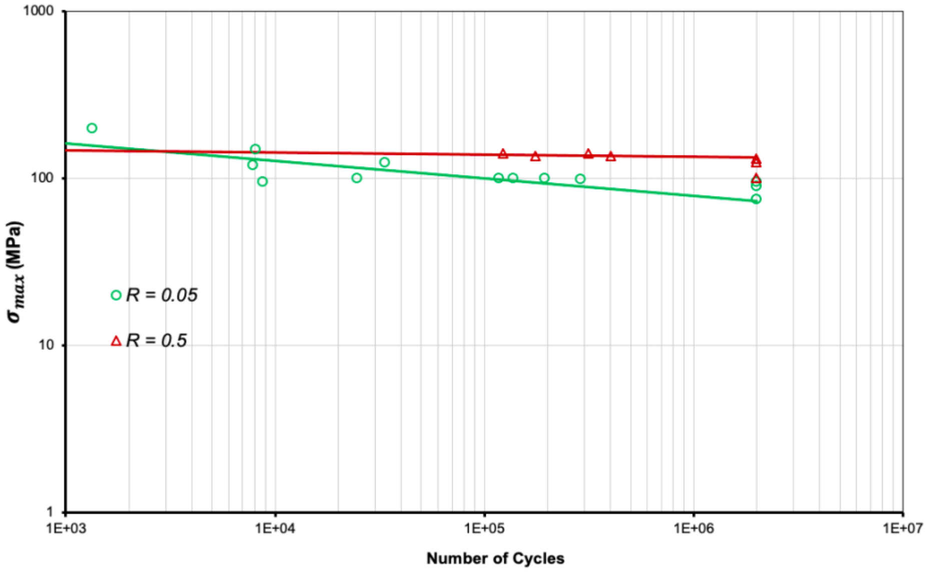

Figure 5- S-N curves obtained for the fatigue tests carried out at R=0.05 and R=0.5, at room temperature (23 ºC), considering the maximum stress applied during the fatigue tests.

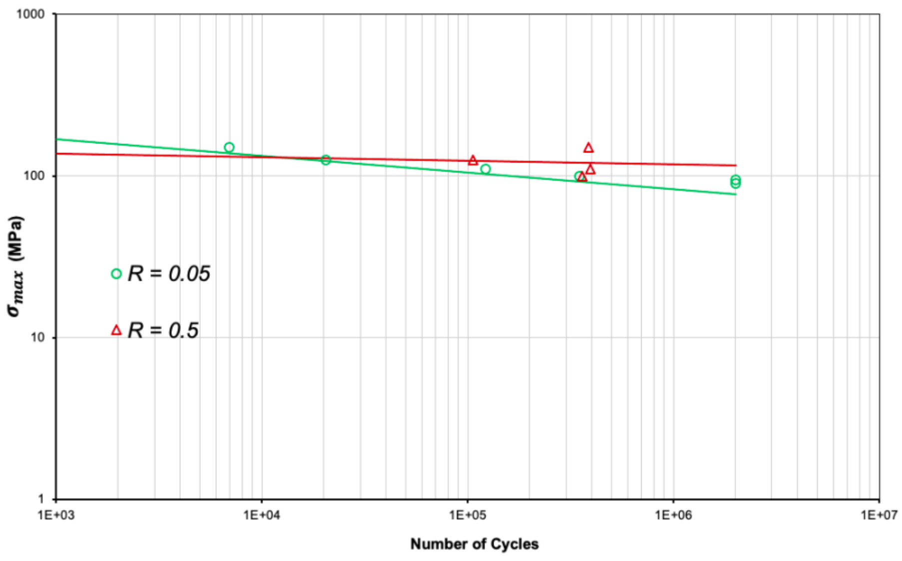

Figure 6- S-N curves obtained for the fatigue tests carried out at R=0.05 and R=0.5, at high temperature (150 ºC), considering the maximum stress applied during the fatigue tests.

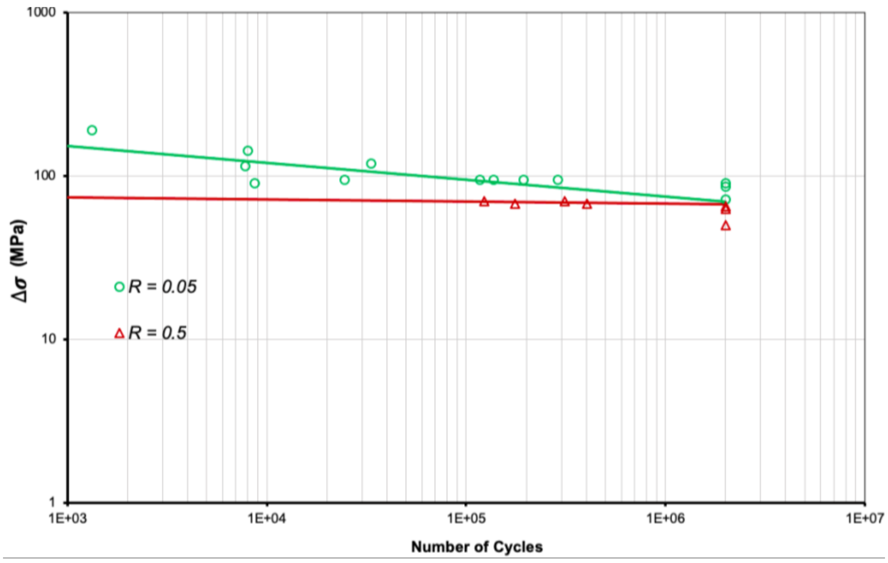

Figure 7- S-N curves obtained for the fatigue tests carried out at R=0.05 and R=0.5, at room temperature (23 ºC), considering the stress range applied during the fatigue tests.

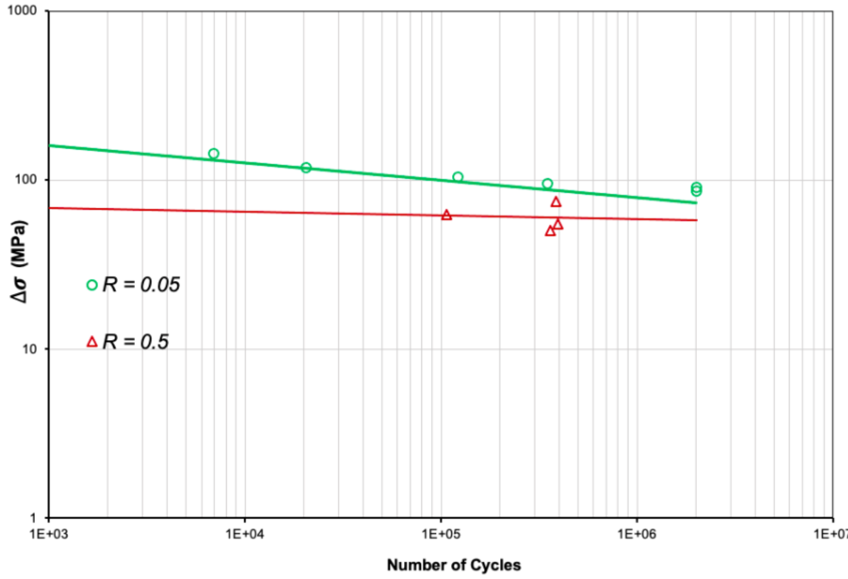

Figure 8- S-N curves obtained for the fatigue tests carried out at R= 0.05 and R= 0.5, at high temperature (150 ºC), considering the stress range applied during the fatigue tests.

The fatigue life of the specimens was found to be lower when the lowest stress ratio (R= 0.05) was applied, when taking into account the maximum stress applied during the tests. This means that for the same number of cycles, the maximum stress needed to cause failure in R= 0.05 conditions is lower comparatively to the one required for R= 0.5 conditions. Relatively to the stress range, the lowest stress ratio was found to result in a higher fatigue life of the specimens. This trends were observed for both loading temperatures. Regarding the temperature effect over the fatigue life of the specimens, it is also easy to perceive the negative impact of the use of 150 ºC as testing temperature: when the same stress ratio and maximum stress (or similar) were applied to the specimens at room temperature, fatigue failure occurred at a significantly higher number of cycles, comparatively to the ones obtained at 150 ºC. Such a trend was expected, taking into account the work developed by Resan et al. [2] and Tra et al. [3].

The material was also found to be sensitive to mean stress applied, since the S-N curves obtained for the maximum stress were less spaced that the ones obtained for the stress range, for both loading temperatures.

4. Conclusions

The main conclusions that arose from the work that was developed are the following:

- Both samples presented a W-shaped hardness profile which is characteristic of friction stir welds of heat treatable aluminum alloys .
- Regarding the UTS, similar values were obtained for the three specimens that underwent uniaxial quasi-static tensile tests, with an average of 365 MPa (standard deviation of 11.3 MPa), which corresponds to a joint efficiency of 63%.
- The fatigue life of the AA7075-T651 friction stir welds was found be lower when the lowest stress ratio was applied: R= 0.05, considering the maximum stress applied, at both loading temperatures. The contrary was also found to be true, for the stress range applied.
- The fatigue life of the specimens at the higher loading temperature was significantly lower when compared to fatigue tests conducted at a similar stress range, with the same stress ratio, at room temperature (23 ºC).

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