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Study of the fatigue behaviour of dissimilar aluminium joints produced by friction stir welding

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ABSTRACT

Building lightweight structures is one of the key strategies to guarantee an efficient, competitive, safe and sustainable public transport system. The implementation of reliable and optimized lightweight structures needs to achieve high levels of performance, cost effectiveness and sustainability. The expected weight saving will significantly reduce fuel consumption and therefore CO_2 emission per passenger-kilometer.

Friction Stir Welding (FSW) is a solid state process enabling to develop new design concepts for lightweight metallic materials, where previously conventional manufacturing processes as riveting or classical welding were used.

This study was conducted within the LighTRAIN project that aims to improve the life cycle costs of the underframe of a passenger railway car, with a novel lightweighted solution. The major objective of the research was to study the fatigue behaviour of dissimilar welded joints based on two different aluminium alloys: AA6082 and AA5754. The paper presents the experimental results obtained in two different structures: AA6082-T6 2 mm and AA5754-H111 2 mm thick joints, and AA6082-T6 2 mm thick joints. Fatigue tests were carried out on lap joints specimens with a constant amplitude loading with a stress ratio $R = 0.1$. The results of the fatigue tests are presented as well as detailed metallographic characterization of the weld zone and also the hardness distribution at the weld region.

Fatigue tests performed on similar and dissimilar joints show low fatigue strength when compared with base materials AA5754 and AA6082, which is associated with the typical "hook" defect inherent to this welding process.

The fatigue performance of AA6082 and AA5754 FSW welded joints suggests a shallower S–N curve than for the similar AA6082 FSW welded joints with an improvement in fatigue performance for lower applied stress ranges.

1. Introduction

The successful development of new welding processes and the good results shown by their applications in light alloys led to an increasing interest on these new technologies by railway companies all over the world.

In order to keep competitive, the railways industry is looking for ways to integrate higher quality materials and processes, while maintaining or reducing costs. Friction Stir Welding (FSW) is perhaps the most remarkable and potentially useful new welding technique to be introduced in the recent past [1].

The first information concerning the use of frictional heat for solid phase welding comes in a form of a United States patent registered over a century ago [2]. Many years have come so far without any relevant technological advance regarding friction welding. However, in the late 20th century, Friction Stir Welding (FSW) was invented. FSW is a solid-state joining process developed and patented by The Welding Institute (TWI) in 1991 [3]. Its development represented a major breakthrough in the metal joining technology field, since it allows welding materials that are hard or even impossible to be welded by common arc-welding methods with good mechanical properties.

FSW is a mechanical process delivering high quality assurance when technological conditions are correctly set-up. Because all the processing takes place in visco-plastic solid phase, all the problems related with solidification of a conventional weld bead are

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avoided. It is clean, ecological, does not depend on operator skills and produces weld seams of the highest quality, while it offers further advantage of being suitable for joining dissimilar metallic materials that were previously extreme difficult, or even impossible to weld by fusion methods without voids, cracking, excessive softening of Heat Affected Zone and/or distortion [4,5].

Some companies are already applying FSW in their products and services pursuing cost savings [6] but the welding of bimetallic materials is a very recent technique [7–9]. Some recent researches have studied FSW of aluminium alloys in dissimilar joints [10–14].

The development and application of FSW technology in lightweight structures in the railway industry provides an effective tool of achieving superior joint integrity especially where reliability and damage tolerance are of major concerns. Since the railway components are inevitably subjected to dynamic or cyclic stresses in service, the fatigue properties of the friction stir welded joints must be properly evaluated to ensure the safety and longevity.

The FSW process parameters have also been proven to affect the tensile strength of the welded dissimilar plate, [15], which have shown to be about 66% of the tensile strength of the aluminium alloy.

Typically, FSW uses two main joint configurations: butt and lap joints. Nevertheless, it has been demonstrated that FSW is still viable with other types of joints namely step joint, flat 90° joint or T-lap joint [5,16]. Lap joints are widely used in assemblies of parts in aerospace and automotive industries.

In this context, this paper deals with the microstructure, mechanical properties and fatigue behaviour of FSW dissimilar and similar lap joints.

The main objectives of this study were the following:

- Produce FSW lap joints in dissimilar and similar conditions with different sets of welding parameters.
- Compare the specimens' experimental behaviour when subjected to static loads, with three different finite element models.
- Obtain S–N curves and determine fatigue life of the specimens made using FSW process.

2. Experimental procedure

2.1. Material and friction stir welding conditions

The materials used in this study were 2 mm thick AA5754 and AA6082 aluminium alloys in H111 and T6 conditions respectively. The material and conditions chosen for this study are currently adopted in the application being studied: rail car structural panels. The mechanical properties of the two aluminium alloys are presented in Table 1.

Dissimilar lap joints of AA5754–AA6082 and similar lap joints of AA6082–AA6082 were produced by friction stir welding and the effect of the welding parameters was investigated. The FSW tool used to produce the welds is a patented modular concept of FSW tool and is composed by three main components: body, shoulder and probe (Fig. 1). This tool enables internal forced refrigeration and the setting of any length for the probe. The tool presents a conical probe with a 4 mm base diameter and a plane shoulder with two striations with outer and inner diameters of 16 mm and 5 mm, respectively.

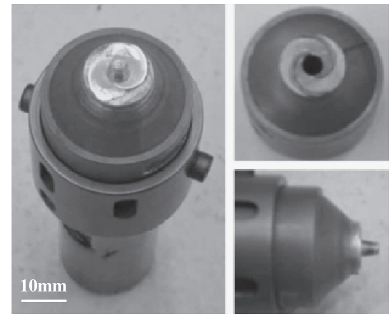

Fig. 1. FSW tool.

The ESAB LEGIO™ 3UL numeric control machine was used to produce the FSW welding joints. Table 2 shows the FSW parameters and controls used to perform all the welds. The welding process was carried out under vertical downward force control. Among the FSW parameters it was decided to vary only three parameters: vertical force tool travel speed and tool rotational speed; since for a given tool geometry and clamping system, these three parameters control the welded seam quality including the weld defects observed [18].

The plates were grinded on contact surfaces in order to remove oxide layers, having been removed about 50 μm of material. The plates were welded in a lap joint configuration and thereafter machined to fabricate the specimens. The specimens geometry used in monotonic and fatigue tests were based on ASTM E8M and ASTM E0466 standards, respectively and are shown in Fig. 2.

In order to select the optimal welding parameters a set of FSW joints were produced by adjusting the vertical force, the tool travel speed and the tool rotation speed in the range of 4000–5500 N, 50–120 mm/min and 800–1000 rpm, respectively. Tables 3 and 4 present the welding parameters used to weld the dissimilar AA5754–AA6082 joints and the similar AA6082–AA6082 joints, respectively.

A metallographic analysis was performed to observe the changes induced in the material by the welding parameters. To this end, samples cut off transversely to the welding direction were obtained. Metallographic analysis comprises a geometrical analysis which aims at characterizing the welding zone.

All samples were attacked with reagent Tucker (HCl, HNO_3, HF and distilled water) and observed under an optical microscope. From the macrographs it was possible identify all the typical structures of the FSW joints, namely, base material (BM), the heat affected zone (HAZ), thermo-mechanically affected zone (TMAZ) and the zone recrystallized dynamically (nugget).

The sample n. 7 of dissimilar condition presents good weld on one side, and a small collage in the opposite side at approximately ¼ of the thickness (Fig. 3a). Taking into account the metallographic observations the sample n. 7 for dissimilar condition (vertical Force = 4900 N; tool travel speed = 120 mm/min; tool rotation speed = 800 rpm) was selected.

The sample n. 3 of similar condition shows a very small collage, slight increase in thickness of the bottom plate and slight thickness

Table 1
Mechanical properties of AA5754 and AA6082 aluminium alloys [17].

Material	Yield strength (MPa)	Ultimate tensile strength (MPa)	Elongation (%)
AA5754-H111	>80	190–240	16
AA6082-T6	>260	>310	7

Table 2
Generic FSW parameters.

FSW control	Vertical force
Rotation direction	CCW
Plunge speed	0.1 mm/s
Dwell time	3 s
Tilt angle	0.5°