International Journal of Fatigue 62 (2014) 77–84

Contents lists available at ScienceDirect

International Journal of Fatigue

journal homepage: www.elsevier.com/locate/ijfatigue

Fatigue assessment of friction stir channels

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ARTICLE INFO

Article history:
Received 31 October 2012
Received in revised form 6 February 2013
Accepted 10 October 2013
Available online 22 October 2013

Keywords:
Friction stir channelling
AA5083-H111
Fatigue tests

ABSTRACT

Friction Stir Channelling (FSC) is an innovative process within solid-state manufacturing technologies able to produce continuous internal or open channels in monolithic plates. The high level of adaptability of FSC makes it possible to apply to many different technical field domains and can bring significant advantages for already existent and new industrial applications. Because engineering components and structures are subject to accidental failures that occur due to unexpected or additional loadings, such as additional axial or torsion, this paper is focused on the effects of multiaxial loading paths on fatigue life of friction stir channelling monolithic plates of AA5083-H111 aluminium alloy.

Uniaxial and biaxial fatigue tests were carried out with a stress ratio of $R = -1$. The FSC specimens used in this study were specially designed for the purpose. The fatigue behaviour was investigated by load controlled tests under uniaxial tension/compression loading and combined axial and torsional proportional loading. Metallographic analysis of the channel microstructure and fractograph analysis of the fracture surfaces were performed by optical microscope and SEM, respectively. For all tests carried out, the first crack always has initiated at the top of the advancing side namely in the boundary between the nugget and the thermo-mechanically affected zone.

1. Introduction

In the recent past, the formation of internal continuous voids defects during Friction Stir Welding (FSW) process gave rise to an innovative solid-state technology – the Friction Stir Channelling (FSC) process – which was firstly proposed as a method of manufacturing heat exchanging devices by Mishra in 2005 [1].

A model based on the flow partition deformational zones for defect formation during FSW was presented by Arbegast [2]. The non-optimal processing conditions or the geometry of the tool features are pointed out as the main causes of the formation of voids in the FSW nugget. The voids formation in the nugget was addressed by the principle of mass balance.

Initially, the FSC process was based on converting the formation of internal continuous voids into a manufacturing technique where all the material removed from the solid component is deposited on the processed zone underneath the shoulder [3]. Recently, Vidal and Vilaça have patented a new technological concept of FSC process [4]. Controlling the amount of material extracted from the interior of the solid component, a distinct material flow is promoted producing the internal channel, discarding the need for a gap between the shoulder and the original unprocessed surface. Therefore, the initial level of the processed surface can be kept and the channel geometry and location can be controlled. However the actual FSC tool shoulder design has advanced to geometries capable to integrate a surface finishing feature [4], the actual state of the art points to there is no need of further finishing operations provided the correct set of parameters is applied.

The stability of the channels along linear and curved profiles was proved by Balasubramanian et al., as well as the possibility of manufacturing Mini Channel Heat Exchangers by FSC, which offers the benefit of being a single step channel fabrication process [3].

The FSC technology has a great potential to be successfully introduced in various industries owing to its high flexibility and low production costs.

This innovative manufacturing process has already been applied in some aluminium alloys, namely in 5 mm thick plates of AA6061-T6 [3], 13 mm thick plates of AA7178-T6 [5,6] and 15 mm thick plates of AA5083-H111 [7]. The FSC parameters are not directly transferable from one aluminium alloy to another [3,5,7], the workpiece material thickness and the thermal conductivity of the materials in contact with the workpiece – anvil and clamping system – influence the cooling rate and the temperature gradients through the material thickness.

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0142-1123/$ - see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.ijfatigue.2013.10.009

The FSC process is a disruptive innovation enabling higher efficiency in energetic applications and advances of structural design of many products. However, FSC still needed to have a considerable development to prove its industrial applicability.

Fatigue failure of mechanical components and structures under multiaxial loading conditions is a common concern, since most engineering components are subjected to multiaxial cyclic stresses in service, and the origins of multiaxiality are generally due to the external loading, the geometry or the residual stresses. In the literature, multiaxial fatigue stresses are classified as two types: proportional loading and non-proportional loading [8]. In proportional loading, the components of stresses vary proportionally with time, and the principal directions remain fixed. In non-proportional loading, the components of stresses vary non-proportionally and the principal directions rotate with time and/or the ratios between principal stresses vary with time.

Up to now, most multiaxial fatigue studies were carried out in different structural materials and multiaxial fatigue models were developed for correlating the experimental results on the specimens, but any was developed using FSC specimens.

In this study the authors investigated the tensile strength, the uniaxial and biaxial fatigue behaviours of FSC specimens.

2. Friction stir channelling

The FSC process results from the application in the visco-plasticized workpiece material of an upward action along the threaded probe combined with an outward action along the scrolled shoulder. The FSC can be controlled by selecting the right processing parameters and tool geometry to soften and deform the workpiece material enabling the creation of a continuous channel. The FSC process relies not only on the frictional heat generated between the tool and the metal workpiece [9], but mainly on the heat energy generated from dissipation during plastic deformation and internal viscous dissipation during the material flow, similarly to heat generation during FSW process [10].

Fig. 1 shows a schematic representation of the FSC process. To perform the FSC process, a non-consumable rotating tool with a specially designed probe and shoulder is inserted into the solid block or plate to be stirred channel and subsequently traversed along its length [5]. During the tool plunge, the rotating FSC tool is forced into the metal workpiece. After the dwell period has passed, the tool begins the forward traverse along a predetermined path, creating a fine grained recrystallized microstructure behind the tool above the channel. Fig. 2 shows a schematic representation of a cross section of a FS channel. A combination of the orientation of the threads on the probe and the direction of tool rotation results in the displacement of material from the probe base to the surface. The flow arm is along the advancing side.

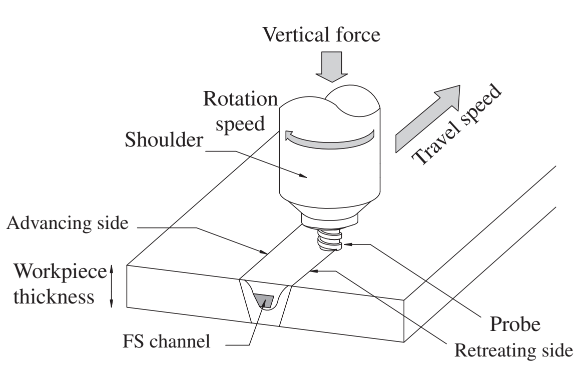

Fig. 1. Schematic representation of friction stir channelling parameters.

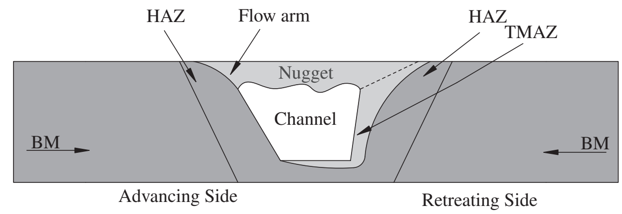

Fig. 2. Schematic representation of a typical cross-section macrograph of a FS channel showing the main microstructural regions: the nugget, the thermo-mechanically affected zone (TMAZ), the heat affected zone (HAZ) and the base material (BM).

3. Experimental procedure

3.1. Material and specimens

The non-heat treatable aluminium alloy strain hardened AA5083-H111 was used in this work. Chemical composition and mechanical properties of this alloy are presented in Tables 1 and 2, respectively.

Friction stir channels were produced on 15 mm thick plates, along the rolling direction, using an ESAB Legio FSW 3UL numeric control equipment. Plunge and dwell periods ($v = 0$) were performed under vertical position control and processing period ($v > 0$) was carried out under vertical force control. A patented modular concept of a FSW tool that enables internal forced refrigeration was used to perform all channels. This tool is based on three main components: body; shoulder and probe. It was selected, for all the runs, a cylindrical probe with an 8 mm diameter and left handed threads along its length and a plane shoulder with one spiral striates scrolling an angle of 360° with inner and outer diameters of 8 mm and 19 mm, respectively (Fig. 3).

The probe was penetrated to a depth of 8.3 mm (without any gap between the shoulder and the workpiece). The tool tilt angle was 0° for all the runs. The tool was rotated in the counter clockwise direction. The FSC parameters selected, after carried out preliminary experimental tests, are presented in Table 3.

Table 1
Chemical composition of 5083-H111 aluminium alloy, % weight.

Al	Mg	Mn	Fe	Cr
93.38	5.26	1.02	0.19	0.15

Table 2
Mechanical properties of 5083-H111 aluminium alloy.

E (GPa)	YS (MPa)	UTS (MPa)	Elongation (%)
70.3	161	302	20

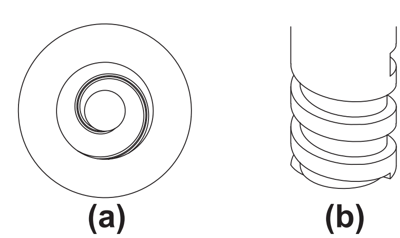

Fig. 3. Schematic representation of the (a) plane shoulder and the (b) cylindrical probe used during FSC trials.