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# Effect of Microstructure on the Fatigue Behavior of a Friction Stirred Channel Aluminium Alloy

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## Abstract

The influence of microstructure on fatigue behavior was investigated on a friction stirred channel strain hardened 5083-H111 aluminium alloy. Friction Stir Channeling (FSC) is an innovative solid-state manufacturing technology able to produce continuous, integral channels in a monolithic plate in a single step. Four sets of FSC parameters were implemented in order to obtain channels with different microstructure and geometry. Fatigue tests were carried out under four-point bending loading. Detailed metallographic, geometric and fractographic analyses were obtained via OM and SEM. It is shown that the fatigue strength is dependent on the channel's nugget (friction stir zone) width.

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Keywords: Friction stir channeling; AA5083-H111; Microstructure; Microhardness; Fatigue behavior

# 1. Introduction

Friction Stir Channeling (FSC) is an innovative process within solid-state manufacturing technologies able to produce continuous, integral channels in a monolithic plate in a single step that was firstly proposed and patented, in 2005, by Mishra as a method of manufacturing heat exchanging devices [1]. Mishra showed that by reversing the

\* Corresponding author. Tel.:+351 218417464. *E-mail address:* catarina.vidal@ist.utl.pt material flow pattern and by selecting the appropriate processing parameters of Friction Stir Welding (FSW), it is possible to produce continuous and stable channels.

The FSC process was initially based on the concept of converting the cavity defect, an internal defect in friction stir welded joints, into a stable manufacturing technique where all the material extracted from the metal workpiece laid on the processed zone below the shoulder, within a clearance between the shoulder and the metal workpiece. In 2009, Balasubramanian *et al.* [2] discussed and demonstrated the applicability of the FSC concept to create continuous channels along linear and curved profiles, as well as the possibility of manufacturing Mini Channel Heat Exchangers (MCHX). In 2011, Vidal *et al.* [3] developed and presented a new concept of FSC process in which the material flowing from the interior of the solid metal workpiece is not deposited on the processed surface but flowed outside from the processed zone in the form of flash self-detachable or easy to extract, keeping the processed surface at the same initial level. In 2013, Rashidi *et al.* [4] introduced a new concept of performing FSC named Modified Friction Stir Channeling (MFSC). In this technique, a non-threaded tool probe with tilt angle and a clearance between the shoulder and the top surface of the metal workpiece are used for extracting material and creating the channel.

In Fig. 1 is presented a schematic representation of the FSC process and tool. To perform the FSC process, a non-consumable rotating tool with a specially designed probe and shoulder is inserted into the metal component 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. The simultaneous rotational and translational motion of the tool during the channeling process creates a characteristic asymmetry between the channel sides. Significant microstructural changes in the stir and thermo mechanically affected zones (TMAZ) have been observed previously [6].



Fig. 1. Schematic representation of the Friction Stir Channeling parameters and tool.

The heat energy that softens the workpiece material, during the FSC process, is generated from dissipation during plastic deformation, internal viscous dissipation during the material flow and dissipation from frictional work between the tool and the metal workpiece.

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.

Considering that fatigue performance is crucial for dynamic loading design of materials and structural integrity and safety, the present investigation aimed to study the effect of microstructure on the channel integrity and fatigue life of friction stir channeling specimens of 5083-H111 aluminium alloy. In this experimental study, the microstructure, microhardness profiles and fatigue behavior of friction stirred channel 5083-H111 aluminium plates were investigated. The results obtained point to a relationship between the fatigue strength and dimension of channel's nugget, with fine equiaxed recrystallized grain. This result could be explained by the calorific energy input during FSC process which influences the amount and hardness of material that is dynamic recrystallized. Based on the fracture surfaces observations, the developing fatigue-crack always initiated at the advancing side into the interior of the specimen.

## 2. Material and methods

The investigated material is the strain hardened aluminium alloy AA5083-H111, one of the highest strength non-heat treatable aluminium alloys, with excellent corrosion resistance. The chemical composition is presented in Table 1. Mechanical properties obtained at room temperature are summarized in Table 2.

Tuble 1. Chemieur composition of 5005-11111 aluminum anoy.						
Element	Al	Mg	Mn	Fe	Cr	
Weight (%)	93.38	5.26	1.02	0.19	0.15	
Table 2. Mechanical properties of 5083-H111 aluminium alloy at room temperature.						
Vickers hardness			92HV0.5			
Yield strength			210MPa			
Ultimate tensile strength			375MPa			
Elongation			18.25%			
Young's modulus			68.9GPa			

Table 1. Chemical composition of 5083-H111 aluminium alloy.

15mm thick plates of AA5083-H111 were friction stirred channel 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.

In order to obtain channels with different microstructure and geometry, four sets of FSC parameters were implemented as shown in Table 3. A modular H13 steel tool that enables internal forced refrigeration was used. This tool is based on three main components: body, shoulder and probe. All tool's arrangement used had a cylindrical probe with 8mm diameter and a 19mm diameter plane shoulder with one spiral. The cylindrical probe used had left handed threads along its length, with a trapezoidal profile, a thread pitch of 3mm and a depth of cut of 0.7mm. The geometric features of the shoulders used are presented in Table 4. The tool was rotated in the counter clockwise direction. The tool tilt angle was 0° for all the runs.

Cross section samples were prepared for macro and microscopic analysis. The samples were ground, polished and then etched with Barker's reagent except U1 samples which were etched with Keller's reagent. Barker's etching was done in a fume cupboard using DC power supply and a voltage of 13V during 2 minutes. U1 samples were observed in a Leica DMI 5000 M inverted optical microscope (OM). All other samples were observed in a Leica DM IRM inverted optical microscope using polarized light. Vickers microhardness tests were performed at mid thickness between the channel top and the upper surface perpendicular to the channeling direction using a 500g load for 10s. In each testing line the microhardness measurements were 1mm spaced.

Tuete S. Theten sur enamering parameters.					
FSC set	Probe length (mm)	Tool rotation speed (rpm)	Tool travel speed (mm/min.)	Vertical force (kN)	
U1	6	1100	50	4	
U2	6	1100	80	2	
L1	8	1100	50	1.5	
L2	8	400	100	2.2	

Table 3. Friction stir channeling parameters

Table 4. Shoulders' geometric features.					
FSC set	Spiral pitch	Spiral height (mm)			
U1	2	0.7			
U2	1	0.7			
L1	1	1			
L2	2	0.7			

Specimens for fatigue tests were manufactured according to the standard E 290-97a [7] requirements as shown in Fig. 2.



Fig. 2. Geometry and dimensions of the fatigue specimens. Details showing the schematic representation of the channels produced with FSC set (a) U1, (b) U2, (c) L1 and (d) L2.

The fatigue tests were carried out on an Instron 8502 servo-hydraulic testing machine with a load cell of 100kN at a range of frequency between 5-10 Hz and a stress ratio R=0.1. The experimental setup is presented in Fig. 3. Fatigue tests were performed in load-controlled mode at constant amplitude sinusoidal four-point bending loading in laboratory air at room temperature.

The applied load, *P*, was calculated by equation (1):

$$P = \frac{\sigma b h^2}{3w} \tag{1}$$

where  $\sigma$  is the maximum stress, b is the specimen's width, h is the specimen's thickness and w is the smallest span distance (30mm).

The specimens were tested with the processed surface under tensile stress and loads were applied out of the processed zone. Tests were performed with the maximum stress levels ranging from 30-150MPa, in order to determine the traditional fatigue *S-N* curves and the fatigue limit  $\sigma_{fSN}$ .



Fig. 3. Schematic representation of the experimental setup.

The specimens were tested until complete failure or to an endurance of 3 million cycles if there was no evidence of fatigue cracking.

After fatigue testing, fracture surfaces of failed specimens were observed in a scanning electron microscope (SEM), in order to analyze its morphology and the crack propagation mechanisms.

#### 3. Results and discussion

#### 3.1. Microstructure analysis

Cross-sectional macrographs of the channels produced according to the parameters described in Table 3 are presented in Fig. 4. The geometry of the channels varies with the process parameters and tool's features. The channel geometry can be attributed to the volume of processed material that is displaced from the base of the probe for every rotation of the tool and also the compacting force that is applied on the channel nugget during the linear forward movement by the shoulder.

The cross-sectional microstructure of AA5083-H111 friction stirred channel was carefully examined by employing optical microscopy in all the four conditions of channeling implemented. The optical microscopy observations performed on the cross-section of the stirred channel samples revealed the distinct changes in microstructures of the zones around the channels.



Fig. 4. Optical macrographs of cross-sections of the channels produced with FSC set (a) U1, (b) U2, (c) L1 and (d) L2.

In all the channels analyzed, the flow of material inside the nugget is evidence of substantial plastic stirring during FSC process. In nugget zone, the microstructure of the material appears as very fine and equiaxed grains in all the channeling conditions (Fig. 5(a), Fig. 6(b), Fig. 7(b) and Fig. 8(b)). During the FSC process, although the thermo mechanically affected zone (TMAZ) undergoes plastic deformation, the heat and deformation are proved to be insufficient for totally recrystallization, and a distinct interface between the nugget and the TMAZ could be obtained as it is depicted in detail (a) of Fig. 6. Base material (BM) microstructure reveals the elongated grains belonging to the rolling process.

On the advancing side (AS), the plastic deformation rate is greater than on the retreating side (RS), microstructure changes quickly from the channel side as can be seen in details (b) and (c) of Figures 5 and 7, respectively. On the other side, on the RS, microstructures from the nugget to TMAZ change more smoothly (Fig. 5(c) and Fig. 7(a)). In the region adjacent to the TMAZ – the heat affected zone (HAZ) – the microstructure is affected by the heat but not by deformation and it is similar to that of BM.



Fig. 5. Optical micrographs from an U1 sample (etched with Keller's reagent).

Based on observations can be inferred that higher vertical forces during the process lead to a more extensive nugget under the channel's base. Micrographs obtained from sample L2 and presented in Fig. 8 revealed a defect on the channel's AS in the interface between the nugget and the TMAZ. This defect is related with the greater removal material rate combined with an insufficient heat input and plastic metal flow caused by a lower tool rotation speed

and a higher tool travel speed. This defect will have significant implications in the fatigue lifetime of the channel produced with FSC set L2.



Fig. 6. Optical micrographs under polarized light from an electrolytic etched U2 sample.



Fig. 7. Optical micrographs under polarized light from an electrolytic etched L1 sample.



Fig. 8. Optical micrographs under polarized light from an electrolytic etched L2 sample.

# 3.2. Microhardness analysis

The microhardness profiles evolution across mid thickness between the channel top and the upper surface are shown in Fig. 9. A softening region having lower hardness than the BM was produced in all friction stirred channel plates above the channel performed. The hardness of the nugget is lower than that of the BM, even though the grain size has decreased.

The hardness values in the nugget are lower than in the BM, but higher than in the TMAZ and HAZ. An increase in hardness in the nugget compared to TMAZ and HAZ points that some work hardening due to intensive stirring has taken place during the channeling process. The samples exhibit a hardness drop in around HAZ and TMAZ indicating that these regions have undergone an annealing process.



Fig. 9. Microhardness profiles of the friction stirred channel samples.

The channels produced at the tool travel speed of 50mm/min. (U1 and L1) exhibit the lowest hardness values in around the HAZ and TMAZ on both AS and RS indicating that the thermal exposure was higher. In addition, the average hardness value in the nugget increases with the decreasing of calorific energy input  $(\propto \Omega/v)$  during the channeling process.

#### 3.3. Fatigue tests

Fig. 10 shows the fatigue life of AA5083-H111 stirred channel specimens in the form of *S*-*N* curves. *S*-*N* curves were obtained by measuring the number of cycles to failure that the specimen supported under a sinusoidal waveform as described in *Section 2*. *S*-*N* curves are presented in log-log scale. Each point represents an experimental test and the curves were obtained by fitting a linear regression equation (2), assuming  $\sigma_{max}$  as the dependent variable:

$$\sigma_{\max} = K_0 N_f^{-m} \tag{2}$$

where  $\sigma_{\text{max}}$  is the maximum stress,  $N_f$  is the number of cycles to failure and *m* and  $K_0$  are empirical constants, namely the exponent and the coefficient of the *S*-*N* curve, respectively.



Fig. 10. S-N fatigue curves at R=0.1 for FSC specimens at room temperature. Four-point bending.

The empirical constants m and  $K_0$  were evaluated and these are presented in Table 5. In order to examine the effect of microstructure on the fatigue behavior, the evolution of the empirical constant  $K_0$  with the nugget width, measured at mid thickness between the channel top and the upper surface, was computed as shown in Fig. 11. For this analysis it was excluded the condition L2, for having revealed a defective condition.

Table 5. Empirical constants $m$ and $K_0$ values.					
FSC set	т	$K_0$			
BM	0.24	3394			
U1	0.21	948			
U2	0.26	1706			
L1	0.21	995			
L2	0.22	538			



Fig. 11.  $K_0$  versus nugget width at mid thickness between the channel top and the upper surface.

The fatigue strength of unprocessed AA5083-H111 is 160MPa. The FSC process is found to be detrimental on fatigue strength of AA5083-H111 as shown in Fig. 10. All specimens with channels without defects (U1, U2 and L1) exhibit very low fatigue strength value. The fatigue strength of FSC specimens without defects in the vicinity of the channel is 50MPa which is 68.75% lower compared to that of the BM. Considering the FSC specimens, for the same maximum nominal stress level, higher fatigue crack initiation periods were obtained for condition U2, as reflected by  $K_0$  value presented in Table 5. From the analysis of Fig. 11 is also possible to verify that  $K_0$  value increases with the increasing of the nugget width, which points that a greater recrystallized zone slows down the fatigue crack initiation. The fracture of all specimens took place in the nugget/TMAZ interface on the AS. This interface is a region of stress intensity between very fine and coarse grains that is amplified by channel corner geometry.

#### 3.4. Fracture surfaces

An examination of the fatigue fracture surfaces does provide useful information concerning the contribution of the microstructural features to the channel's strength. It was selected for presenting the fatigue fracture surface of a FSC specimen L1 tested under a maximum stress of 65MPa as it is depicted in Figures 12 and 13.



Fig. 12. Sequence of SEM fractographs of a region tangent to the advancing side, at increasing magnifications, which show a fracture in a FSC specimen L1 under a maximum stress of 65MPa. The rectangle in fractograph (a) indicates the area that is shown at higher magnification in fractograph (b).



Fig. 13. Sequence of SEM fractographs, at increasing magnifications, which show the other side of the fracture surface of the FSC specimen L1 under a maximum stress of 65MPa. The rectangle in fractograph (a) indicates the area that is shown at higher magnification in fractograph (b).

Fatigue crack propagation on the TMAZ was mainly characterized by fatigue striations along with secondary cracks as it can be observed in Fig. 12. Fatigue ripples can be seen along the surface. There is a clear coexistence of the intergranular fracture mode and the transgranular fracture mode. The fractographs of the nugget presented in Fig. 13 show a smoother fracture surface without evidence of fatigue striations. Some authors [8] attribute this fact to the presence of compressive residual stresses that caused crack closure.

# 4. Conclusions

In the present work a series of AA5083-H111 friction stirred channel plates were produced and analyzed. The microstructure, microhardness and fatigue behavior of the channels were compared and discussed. The four-point bending fatigue tests performed at room temperature show that the fatigue strength of AA5083-H111 friction stirred channel plates depends on the channel's nugget width although, for non-defective conditions, the difference is not very significant. Based on the fracture surfaces observations, the developing fatigue-crack always took place in the nugget/TMAZ interface on the AS. This interface is a region of stress intensity between very fine and coarse grains that is amplified by channel corner geometry.

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