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Fatigue behaviour of AA6082 friction stir welds under variable loadings

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ABSTRACT

Welded components are often subjected to variable amplitude service loads, demanding fatigue life prediction methods that can take into account fatigue damage accumulation. In previous work the fatigue behaviour of friction stir welding of aluminium alloys under constant and variable amplitude loadings was analysed under the stress ratio $R = 0$. The objective of this work is to extend the study of the fatigue strength of friction stir welds in AA6082-T6 under constant and variable amplitude loadings under the stress ratio $R = -1$ and analyse the validity of Minerśs and Manson–Halford damage sum rules for both stress ratios $R = 0$ and $R = -1$. Fatigue tests were carried out in a servo-hydraulic testing machine using typified Gassner amplitude spectra, ranging the correspondent shape exponent between 1.5 and 5. Constant amplitude fatigue tests revealed that crack initiation occurs internally from tunnel defects or at the surface, near stress concentration due to shear lips, leading to fatigue life reduction relative to the base material. Tunnel defects showed to be more detrimental for fatigue resistance than the stress concentration created near shear lips. As expected, a significant mean stress influence was observed. Therefore, the assumption in design codes of no mean stress effect, based in the presence of high residual stresses close to the yield stress, seems not adequate to be applied for friction stir butt welds. Although residual stresses were not measured in this work, the small test samples ($160 \times 15 \times 4$ mm) tested transversely implies that they must be very small. The comparison of experimental fatigue lives with predictions calculated with both Minerśs Linear Damage Rule and Manson–Halford Double-Linear Damage Rule, using two stress ratios and four spectrum shape factor values, revealed a good agreement for $R = 0$. Under $R = -1$ both damage predictions methods were, in general, unconservative, with the Double-Linear Damage Rule being less unconservative. Therefore, the application of the Double-Linear Damage Rule can be considered advantageous as it requires no further input information than the required by the Linear Damage Rule and takes into account both loading level and loading sequence effects.

1. Introduction

Considered as the most significant development in metal joining in the last decade, friction stir welding (FSW) is a joining process with good energy efficiency, environmentally friendly and versatile. A significant amount of research was carried out in several fields and different materials since the invention of this technique in 1991 [1]. Generally, FSW specimens have higher fatigue resistance than specimens welded by metal inert gas (MIG) and tungsten inert gas (TIG) processes [2–6]. Ericson and Sandstrom [2] compared fatigue results of friction stir welds with data obtained for conventional arc-welding methods, namely, MIG-pulse and TIG processes in the 6082 aluminium alloy (T6 and T4 conditions), It was observed that MIG-pulse and TIG welds presented both lower static and fatigue strength than the friction stir welds. Moreira et al. [3,4] also compared the fatigue behaviour of joints performed by the traditional process of metal inert gas (MIG) welding and by the friction stir welding process, observing that friction stir welded and MIG welded specimens had lower yield and ultimate stresses than the base material. Friction stir welded specimens also presented higher fatigue lives than MIG welded specimens. Kobayashi et al. [5] performed fatigue tests on an extruded shape base material with FSW and MIG welds. It was observed that both the FSW and the MIG joints presented lower tensile strength than the base material. Furthermore, the MIG joints tensile strength was also lower than the one for the FSW joints. In general higher lives for the friction stir welds in comparison with MIG welds was also observed [5]. In previous work [6] it was also observed that FSW leads to a decrease of the AA6082-T6 mechanical properties relative to the base material. Furthermore, an important hardness decrease in the thermo-mechanically affected zone and the nugget zone average hardness was found. FSW of AA6082-T6 specimens presented lower fatigue

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lives than base material, but higher fatigue resistance than specimens welded by the MIG and TIG processes. A good agreement was observed between constant and variable amplitude fatigue tests, when the equivalent stress, calculated according to Mineŕs rule was plotted against the number of cycles to failure. The damage sum ranged between 0.5 and 1.5 for a stress ratio $R = 0$ under four different spectrum loadings.

In comparison with the IIW design curve [7] for a similar fusion welds joint detail, FSW welds presented conservative fatigue results, indicating that a higher class than FAT class 40 could be attributed to butt joints welded by FSW. One of the reasons for the codes to be highly conservative is related to the assumption of no mean stress effect, based in the presence of high residual stresses close to the yield stress. However, in the literature there are several works observing that residual stresses observed in FSW are significantly lower than the ones obtained in conventional welding processes [8,9]. Lemmen et al. [8] performed residual stress measurements in AA2024-T3 friction stir welds using X-ray diffraction, observing that FSW introduced significant residual stresses in the longitudinal direction, i.e., parallel to the weld, but negligible stresses in the transverse direction, i.e., parallel to the loading stresses. Lanciotti and Vitali [9] obtained lower values of residual tension stresses than those typically measured in welded aluminium alloys by conventional processes, concluding that FSW produced tension residual stresses of only about one half when compared with those obtained in the aluminium alloy 2219-T851 welded by plasma arc. They also observed that the volume of the material affected by residual stresses was much lower in the friction stir welds. Also, James et al. [10] presented an interesting work where residual stresses where measured, in 8 mm 5053-H321 aluminium plates welded by FSW using double pass, by the synchrotron radiation technique in both longitudinal and transversal directions for tree depths (1, 4 and 7 mm). Residual stresses were obtained in the as welded condition and also after a single loading cycle and after 100 loading fatigue cycles, in order to analyse the effect of fatigue cycling on the residual stress fields. In the as welded condition tensile peak stresses are lower than 30 MPa and significantly higher compressive residual stresses were obtained. James et al. [10] also found, as prime effect of fatigue bending loading, a significantly increase of both tensile and compressive peak residual stresses together with a translation of the residual stress field to the tensile side. This behaviour was observed in a cyclically hardening alloy and therefore for an aluminium alloy with an opposite stress–strain cyclic behaviour the effect of fatigue loading on residual stresses variation can be quite different and that the volume of the material affected by such stresses was much lower when compared with those obtained in the aluminium alloy 2219-T851 welded by plasma arc.

The majority of the studies relative to fatigue behaviour of friction stir welds have been limited to constant amplitude loading [2–5]. However, welded components are often subjected to variable amplitude service loads, demanding for fatigue life predictions methods that can take into account fatigue damage accumulation. The treatment of this phenomenon has received increasingly attention since Palmgren–Mineŕs (PM) accumulation rule was introduced in 1945 [11]. More than 50 fatigue damage models have been proposed since then. PM is both load-level and load-order independent due its linear nature. Life losses of five to ten times or more have been reported in the literature [12]. Despite the improved accuracies of the new models, they have not been used in structural design. This lack of use is partially due to the requirement for specific constants that need to be experimentally obtained. The double linear damage rule (DLDR), introduced by Manson [13] and later enhanced in 1981 [14], avoids the linear damage rule (LDR) shortcomings, requires only twice the effort of the classic LDR, retains the LDR simplicity and no experimental constants have to be evaluated to apply this model. Halford [15] compared LDR and DLDR and proposed a criterion for judging loading circumstances when classical linear damage accumulation becomes unacceptably nonconservative. An increase of accuracy of the DLDR is expected when there is an appropriate mixture of low-cycle fatigue (LCF) and high-cycle fatigue (HCF) loading. Furthermore, it is also expected an increasing deviation from linearity of damage accumulation when the lives in LCF and HCF are more apart.

The objective of this study is to analyse the fatigue strength of friction stir welds in AA6082-T6 under constant and variable amplitude loading for the stress ratio $R = -1$ and to compare experimental fatigue lives with predictions calculated with both Minerś̀s [7] LDR and Manson and Halford [14] DLDR for $R = -1$, as well as for $R = 0$, under several spectrum severity values.

2. Experimental details

2.1. Preparation of welds

The material used for this research was the heat treated AA 6082-T6 aluminium alloy. T6 age-hardened condition is obtained by solution treatment, quenching and artificial age-hardening. Table 1 presents the alloy chemical composition while Table 2 presents the main mechanical properties [16]. Fig. 1 depicts the *FSW* tool used in the friction stir welds which geometry is characterized by a 5 mm diameter left threaded cylindrical pin and a 16 mm diameter shoulder. The friction stir welds were performed perpendicularly to the rolling direction in an aluminium plate with 4 mm thickness.

The machine used for performing the welds only had position control, which only allowed position control of the tool. Neither load control or load monitor was possible with this machine. The welds were performed choosing the following parameters: welding speed of 300 mm/min, tilt angle of 2° and rotating speed of 1500 rpm. More detailed information can be found in [6]. The presence of defects in the welds, like root flaws, tunnel or lack of penetration defects, was analysed by metallographic observation of cross-sectioned surfaces, perpendicular to the welding direction of the welds. Initially, the welds were performed with only a single welding pass. With this method part of the welded plates presented tunnel defects, with size ranging between 100 and 500 μm, formed mainly in the advancing side, which can affect the fatigue resistance, depending of both defect size and shape. cted by microscopy observation. Although welds with improved quality could be obtained using different parameters or other tool geometry, the procedure adopted in this work to avoid the presence of the tunnel defects with a single pass, was to weld some plates with two overlapping passes in the same side of the plate and using the same tool and parameters used in the single pass welds. Fig. 2a and b shows examples of welds obtained with a single pass and two successive passes, respectively. Fig. 2a present a poor quality welded plate, presenting a tunnel defect size of about 400 μm, while Fig. 2b shows the cross section where no defects were detected by microscopy observation. The tunnel defects tend to appear in the advancing side of the nugget lower zone near the thermo-mechanically affected zone and they are continuously formed in the weld direction. The size of these defects, typically

Table 1
Chemical composition of AA6082-T6 aluminium alloy (wt.%) [6].

Si	Mg	Mn	Fe	Cr	Cu	Zn	Ti	Other
1.05	0.8	0.68	0.26	0.01	0.04	0.02	0.01	0.05