Engineering Fracture Mechanics 76 (2009) 134–148

Contents lists available at ScienceDirect

Engineering Fracture Mechanics

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

Fatigue life predictions using fracture mechanics methods

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ARTICLE INFO

Article history:
Available online 5 August 2008

This paper is dedicated to the memory of Arij de Koning who passed away the 6th of February 2007.

Keywords:
Fracture mechanics
Fatigue life prediction
Pre-corrosion
Friction stir welding
Variable amplitude loading
Cold expansion
AFGROW
NASGRO

ABSTRACT

In the present work, a simple engineering approach which is based on a relatively solid background and which is checked against fatigue test data for various test conditions was developed: it may provide a practical and reliable basis for the analysis of structures under in-service loading conditions, in the presence of previous corrosion attack, or in the presence of a residual stress field, by using widespread fracture mechanics software. In particular, the approach was checked against an experimental program which consists of the following fatigue tests: base and friction stir welded (FSW) material under constant amplitude loading at different loading ratios ($R = 0.1, 0.5, -1$); pre-corroded base and FSW material under constant amplitude loading at load ratio $R = 0.1$; centre hole FSW specimens under the standardised variable amplitude loading spectrum FALSTAFF. Moreover, from the literature fatigue experiments under FALSTAFF of cold expanded as well as not cold expended holes were also used to validate the approach. The predictions were performed with the last version of AFGROW and NASGRO 3.0 software.

1. Introduction

In general, structures contain micro structural defects such as porosity, voids, discontinuities which can lead to the formation of cracks if the service loading exceed a certain level. Once a crack is present, it may grow in a stable manner and after a certain time results in an unstable crack growth and eventually in the ultimate failure of the structure. Fatigue is one of the most difficult, and insidious, design issues to resolve. Experience has shown that the majority of structural failures occur as a result of fatigue: the percentage of such failures in mechanical components is set around the order of 90%. In the aerospace industry, the introduction of damage tolerance requirements has been a milestone in the design of fatigue resistant structures and it was possible only thanks to the level of maturity that linear elastic fracture mechanics has reached. Many crack growth prediction models have been proposed and used by the industrial and scientific community [1,2]. The calculations of this work were performed with AFGROW [3], ESACRACK 4 [4], and NASGRO 3.0 [5]. More recent versions, NASGRO 5.2, exist, NASGRO 3.0 was the version available at the time the work has been performed. AFGROW is a computer program developed by the US Air Force and is available on line. ESACRACK 4 was written by ESA and NASA and NASGRO 3.0 was created by NASA. Since NASGRO 3.0 is also part of the ESACRACK 4 software package, in the following just AFGROW and NASGRO 3.0 will be compared. Both software need the same initial data to perform the crack growth analysis: the crack geometry, the loading conditions, the $da/dN - \Delta K$ crack propagation curve of the material as well as static and fracture toughness properties (which can be found in a large database of the software or can be implemented by the user). The programs then use implemented K-factors solutions and crack growth concepts to propagate the crack until failure occurs. During the last three

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[1] The work has been performed during the author's stay at the Institute of Materials Research of the DLR in Cologne, Germany.

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doi:10.1016/j.engfracmech.2008.07.008

decades considerable work has been devoted to understand the fatigue crack propagation under constant amplitude loading. However, the basic problem is to predict fatigue crack growth in real structures of complex geometry under in-service loading conditions. Fatigue loads in-service generally imply a randomly variable amplitude, rather than constant amplitude loading. Different types of load sequences are known to induce a number of different load interaction effects [6,7], which can result in significant variation on the crack growth rate. Moreover, it is well known that corrosion unfavourably affects the structural integrity since fatigue cracks nucleate from corrosion pits [8,9], drastically reducing the fatigue life of the component. The computation effort is more complex for structures which are affected from the presence of a residual stress field. Residual stresses are, in many cases, an undesired consequence of the manufacturing and joining technologies adopted (welding, cold forming) or, in other cases, are intentionally produced by means of proper techniques (e.g. shot peening, cold working) with the aim of improving strength. All these effects should be included in the predictions as they can affect structural health of structures. For practical applications, industrial designers require reliable prediction models, easy to handle, without too many empirical constants (derived from specific tests) and, lastly, capable of running in a reasonably short time on personal computers. In previous works the authors have successfully demonstrated the capability of the previously mentioned software to predict the crack growth life of pristine and welded specimens, both under constant and amplitude loading spectra [10–12].

The aim of the present work is to demonstrate the possibility of applying fracture mechanics methods to perform fatigue life predictions. The calculations were compared with experimental results. The following experimental test program was carried out:

- Constant amplitude loading fatigue tests of base and FSW material of un-notched specimens at different loading ratios ($R = 0.1, 0.5, -1$).
- Constant amplitude loading tests of pre-corroded base and FSW material at load ratio $R = 0.1$.
- Variable amplitude loading fatigue tests of centre holed FSW specimens under FALSTAFF.
- Variable amplitude loading fatigue tests of centre holed cold expanded specimens under FALSTAFF.

In predicting the fatigue life of base and friction stir welded structures a basic assumption was done: the crack is starting from constituent particles and particle clusters; moreover, in order to apply to fatigue the fracture mechanics statements, it was also assumed that the cracks formed immediately at the particles and the entire fatigue life was comprised of crack propagation.

The pre-corroded base as well as friction stir welded materials were simulated by identifying and quantifying the widespread corrosion damage by many metallographic sections. A model was then developed which creates a single surface crack having the deepest and largest corrosion attack as dimension. In the model no distinction was done between the two observed corrosion types, i. e. pitting and inter-granular corrosion. In predicting the fatigue life of the centre holed FSW specimens under FALSTAFF the same assumptions regarding the starting cracks as the un-notched specimens were adopted, and the load sequence effects were taken into account by using the Willenborg retardation model [13]. Because of the small size of the specimens, the very low transverse residual stresses were not considered.

In the calculations for the cold expanded holes, since the residual stresses were too high to be neglected, the Willenborg model was used in combination with a residual stress profile in specimen thickness as well as width direction obtained by fitting the X-ray diffraction measurements.

2. Experimental program

2.1. Friction stir welding and specimen geometry

Four millimeter thick AA 2024-T3 material was provided from Pechiney, in the form of sheets. Table 1 gives a survey of the chemical and mechanical properties of the alloy investigated in the experimental procedure. The FSW butt joints were produced at the DLR, the German Aerospace Centre following the TWI patent [14]. All the welds were performed parallel to the rolling direction of the sheets. The material was welded in T3 condition and no additional heat treatment was carried out after the welding procedure. The welding speed was 300 mm per minute, the rotating speed of the tool was 850 revolutions per minute and the tilt angle was kept constant at 0°. The welding parameters used to produce the joints are summarised in

Table 1
Chemical composition and mechanical properties of the alloys investigated

Alloy	Si	Fe	Cu	Mn	Mg	Cr	Zn	Ti	Zr
Chemical composition of the alloys in wt%									
AA 2024-T3	0.50	0.50	3.8–4.9	0.3–0.9	1.2–1.8	0.1	0.25	0.15	–

Material	R_{p0} (MPa)	R_m (MPa)	E	Elongation (%)
Mechanical properties				
AA2024-T3	329	476	72000	25.7