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Evolution of residual stresses with fatigue loading and subsequent crack growth in a welded aluminium alloy middle tension specimen

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Abstract

Neutron diffraction has been used to measure the evolution of the residual stresses in a VPPA welded Al-2024 alloy middle tension ($M(T)$) specimen with fatigue loading and subsequent crack growth. The measurements were carried out on the diffractometer ENGIN-X, a time-of-flight instrument, at the ISIS Pulsed Neutron Source. Fatigue crack growth was performed in situ and strain measurements averaged through the thickness of the specimen were made along two orthogonal directions as the crack grew, allowing the stresses in the specimen to be calculated assuming plane stress. 2D finite element simulation of the evolution of the initial residual stress field with crack growth, using an elastic model produced predictions that were in reasonable agreement with the experimental results. The results further indicate that some re-distribution of the residual stress field occurred due to the crack tip plasticity associated with the fatigue loading.

Keywords: Residual stresses; Neutron diffraction; Weld; Fatigue crack growth

1. Introduction

Welded structures are increasingly being considered and utilised by the aerospace industry as the technology permits larger integral structures to be manufactured and hence the cost and the weight of the final product can be reduced.

However, unlike riveted structures, welded structures typically contain no crack stoppers that can act to retard crack propagation. Another inherent inconvenience with welds are the residual stresses caused by the intense local heating. These stresses can significantly influence the fatigue life of engineering components [1].

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While it is clear that residual stresses affect the fatigue behaviour of many components and structures, it is not trivial to predict quantitatively how a given residual stress field will accelerate or retard fatigue crack growth rates. This has obvious implications for lifing assessments of components where a damage tolerant approach is adopted, assuming a known fatigue crack growth rate and load cycle characteristics. A tensile, accelerating stress field can lead to a non-conservative prediction of the components life, while a compressive residual stress could give a over-conservative life prediction.

Linear elastic fracture mechanics is the approach most frequently employed to account for the effect of an existing residual stress field on fatigue crack growth rate [2]. It is assumed that the principle of superposition is valid and that the residual stresses are not affected by the presence and growth of a fatigue crack [3]. Recent improvements in non-destructive measurement techniques [4] and in the application of weight or Green's functions methods to include residual stress fields into stress intensity factor (SIF) calculations [5] based on Bueckner's principle [6] have both enabled predictions of the effects of residual stresses on fatigue crack propagation to be made more readily. However, whilst the final crack growth lives are accurately predicted, the form of the crack length versus cycles curve is typically quite different from the test result with the initial crack growth being underestimated and the later crack growth being over estimated [4,7].

It has furthermore been suggested that one of the reasons for that predicting damage tolerance lifetimes in the presence of strong residual stress fields is difficult, is the residual stress re-distribution associated with the fatigue loading. This may occur due to the interaction between the plasticity that accompanies the fatigue crack and the misfit strains that induced the original residual stress field [4,8].

Detailed knowledge of the evolution of residual stresses with fatigue crack growth therefore has to be determined in order to be able design a damage tolerant structure. Several authors [9–12] have attempted to measure the residual stress relaxation that occurs with crack growth. However, the "crack" was extended by machining a notch in the specimen. Under these circumstances there is no fatigue induced plasticity which will affect the residual stress redistribution. In addition, a machined notch, in contrast to a fatigue crack, cannot withstand a compressive traction and hence compressive residual stresses are relieved.

Neutron diffraction has been used for measurement of residual stresses in various types of materials and industrial components [13,14]. The method has been extensively applied to measure residual stresses in welds [15–19] as the stresses are usually high, the gauge volume typically used is small compared with the weld and the penetration depth is large. Furthermore, the method is non-destructive, which makes it ideal for monitoring residual stress fields in fatigued samples. In this work the evolution of the residual stresses with fatigue crack growth in a VPPA welded aluminium alloy $M(T)$ specimen has been evaluated using neutron diffraction by growing a fatigue crack in situ using a servo hydraulic fatigue machine placed on the neutron diffractometer. The results are compared to predictions obtained from a 2D FE simulation of the evolution of the initial residual stress field with crack growth.

2. Experimental procedures, materials and results

2.1. Material and specimen geometry

Single pass autogenous variable polarity plasma arc (VPPA) welding was used to manufacture 2024 aluminium plates 500 mm $\times$ 500 mm. The plates were welded with the weld direction parallel to the rolling direction of the plate. The aluminum alloy 2024 (composition as shown in Table 1), heat treated to T351 specification was studied. In the T351 condition, the material is solution treated, quenched, stress relieved by 1.5–2% stretching

Table 1
The typical composition (wt.%) and mechanical properties of Al-2024–T351 alloy

Cu	Mg	Mn	Tramp elements (Cr + Zn + Fe + Zr)	Al	Mechanical properties
3.7–4.5	1.2–1.5	0.15–0.8	<0.75	Balance	YS[a] 360 MPa UTS[b] 480 MPa

[a] Yield stress.
[b] Ultimate tensile strength.