International Journal of Fatigue 33 (2011) 588–596

Contents lists available at ScienceDirect

International Journal of Fatigue

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

Evaluation of the intrinsic crack growth rates of weld joints

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ARTICLE INFO

Article history:
Received 13 May 2010
Received in revised form 27 October 2010
Accepted 28 October 2010
Available online 3 November 2010

Keywords:
Welded joints
Crack growth
Residual stresses
Weld intrinsic property

ABSTRACT

A method is presented for evaluating the intrinsic fatigue crack growth rate (FCGR) by excluding the effect of welding-induced residual stresses. Calculation procedures have been developed and demonstrated via an example of crack growth across a longitudinal weld subjected to constant amplitude loads and also constant applied stress intensity factor ranges. Trends of intrinsic FCGR in different weld regions are identified. The methodology should also be applicable for crack propagation within and parallel to a weld for establishing intrinsic FCGR laws.

1. Introduction

Significant amount of research has been conducted in the past 20 years to understand the damage tolerance properties of fusion, laser and friction stir welds in aerospace aluminium alloys [1–9]. One of the key damage tolerance requirements is the capability of predicting fatigue crack growth life. Comparing with the base material (BM), changes in crack growth rates in weld metal (WM) arise from two main factors, one is the welding-induced residual stresses and the other is the change in weld metal properties due to the microstructural changes. However, current predictive models uses the base material fatigue crack growth rate (FCGR) and consider only the residual stress to predict weld plate life; changes in weld metal properties are not counted in these predictive models [3,9–12]. The main reason for this is the lack of weld metal crack growth rate properties.

For crack propagation perpendicular to a weld, welding-induced residual stresses are found to play a major role on the FCGR [1,7,8]. Effects of residual stress and microstructural changes on FCGR were investigated in friction stir welded AA2050 [7] and AA2024 alloys [8]. The tests were conducted on compact tension specimens subject to constant values of applied stress intensity factor range. Both studies have concluded that residual stress is the main influential factor, but in the weld nugget microstructural effect is also present. In [8], effect of microstructural and hardness changes on FCGR was observed by relieving weld residual stresses. The test specimen was stretched parallel to the weld centreline to a 2% plastic strain. It was observed that crack growth rates outside the weld rose to the values expected for the BM. Since no difference was found in the hardness and microstructure before and after the residual stress relief, it was concluded that residual stress redistribution after the mechanical tensioning was responsible for the difference in crack growth rates. However, no quantitative analysis has been performed on the influence of each factor.

For crack propagation within and parallel to a weld, crack growth rates have been found to be considerably lower than that in the base material [5,13]. A detailed FE model was used to simulate crack path deviation in weld by employing different material properties for the base material and weld metal [14]. However, no method has been found in the open literature for predicting fatigue crack growth behaviour within a weld. An approximate method is to use the weld metal FCGR measured from test coupons (instead of using the base material FCGR and adding residual stresses) to predict the life of a welded component that is manufactured by the same welding process. Using this method the effects of residual stress and microstructural changes are both included in the coupon test data. However, the predicted crack growth rates can be sensitive to the difference in specimens' geometry and dimension.

It is well-known that residual stress magnitude and distribution are different for different dimensions, but the weld metal microstructural change should be the same for the same welding process parameters even though the dimensions of the test coupon and component are different. Therefore, if the influences of residual stress and weld microstructure change on FCGR can be separated, that is if the FCGR in a weld can be determined without the influence of residual stress, then it is possible to evaluate the influence

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doi:10.1016/j.ijfatigue.2010.10.014

Nomenclature

a	half or full crack length in centre crack or edge crack geometry
$A_1, \ldots, A_n$	base material constants in general form of crack growth laws
$A'_1, \ldots, A'_n$	weld metal constants in general form of crack growth laws
C, m, n	material constants in the Walker Equation
C_b, m_b, n_b	base material constants in the Walker Equation
C_w, m_w, n_w	weld metal constants in the Walker Equation
E, G, v	Young's modulus, Shear modulus, Poisson's ratio
$K_{app}, K_{res}, K_{tot}$	Stress intensity factor (SIF) due to applied, residual and combined stress fields
$K_{app,\max}, K_{tot,\max}$	SIF due to applied and combined stress fields at the maximum applied stress
$K_{app,\min}, K_{tot,\min}$	SIF due to applied and combined stress fields at the minimum applied stress
$\Delta K_{app}, \Delta K_{tot}$	SIF range due to applied and combined applied and residual stresses
R	nominal stress intensity factor ratio ($K_{\min}/K_{\max} = \sigma_{\min}/\sigma_{\max}$)
R_{eff}	effective stress intensity factor ratio ($K_{tot,\min}/K_{tot,\max}$)
W	half width of centre crack or full width of edge crack specimen
β	non-dimensional SIF
$\Delta\sigma_{app}, \sigma_{app\max}$	applied stress range and maximum stress
$\sigma_{res}(x)$	residual stress distribution
$(da/dN)_b, (da/dN)_w$	fatigue crack growth rate (FCGR) in base material and weld metal
$(da/dN)_R$	FCGR in weld metal with residual stress effect only (no material change)
$(da/dN)_{int}$	intrinsic FCGR in weld metal without residual stress effect

of the weld material intrinsic property on the FCGR. This growth rate property should be unique for each welding process and independent of weld sample geometry and residual stress, therefore it can be used in conjunction with either measured or calculated residual stresses for predicting crack growth life of a give component (using coupon test data). In this paper we refer this property as the "weld intrinsic crack growth rate".

The objective of this paper is to present a method to extract the weld intrinsic crack growth rate from test measured crack growth rate. The idea is that, if it is possible to separate the contribution of welding-induced residual stress from measured crack growth rates, then the rest in the growth rate change is due to the contribution from weld metal microstructural changes. First, fracture mechanics analysis is performed to determine the residual stress effect on FCGR in the base material. This is followed by a series of calculations to extract the weld intrinsic crack growth rates from measured FCGR. An example is used to demonstrate the methodology and analysis procedure.

2. Methodology

2.1. The concept

In the presence of residual stresses, the total stress intensity factor range and effective stress intensity factor ratio due to the combined stresses can be calculated by the superposition rule [15,16]:

$$\Delta K_{tot} = K_{tot\max} - K_{tot\min} = (K_{app\max} + K_{res}) - (K_{app\min} + K_{res}) = \Delta K_{app} \tag{1}$$

$$R_{eff} = \frac{K_{app\min} + K_{res}}{K_{app\max} + K_{res}} \tag{2}$$

It can be seen that ΔK_{tot} is the same as ΔK_{app}, but R_{eff} is different from the nominal ratio R. In the framework of linear elastic fracture mechanics (LEFM), numerous crack growth rate laws have been developed to correlate FCGR (da/dN) with the stress intensity factor range ΔK [12–13]. The general form of these laws can be expressed by Eq. (3), where $A_1, \ldots, A_n$ are material constants of the base material, ΔK_{app} and R reflect the applied stress and specimen geometry.

$$\left(\frac{da}{dN}\right)_b = f(\Delta K_{app}, R, A_1, \ldots, A_n) \tag{3}$$

When the crack growth law is applied to calculate crack growth rates of welded samples, ΔK_{app} and R are replaced by ΔK_{tot} and R_{eff} to include welding-induced residual stresses; $A_1, \ldots, A_n$ should be replaced by $A'_1, \ldots, A'_n$, which are material constants of the weld sample.

$$\left(\frac{da}{dN}\right)_w = f(\Delta K_{tot}, R_{eff}, A'_1, \ldots, A'_n) \tag{4}$$

The difference in the FCGR between the weld metal and base material is:

$$\Delta = \left(\frac{da}{dN}\right)_w - \left(\frac{da}{dN}\right)_b \tag{5}$$

This difference contains contributions from the weld residual stresses and material property changes in the weld. Assume that the welding process induces only the residual stress without changing the material properties, the corresponding FCGR should be:

$$\left(\frac{da}{dN}\right)_R = f(\Delta K_{tot}, R_{eff}, A_1, \ldots, A_n) \tag{6}$$

The increment in FCGR caused by residual stress effect is:

$$\Delta_1 = \left(\frac{da}{dN}\right)_R - \left(\frac{da}{dN}\right)_b \tag{7}$$

Since Δ_1 should be different from Δ, define Δ_2 as the difference due to the contribution of weld material change without the influence of residual stress:

$$\Delta_2 = \Delta - \Delta_1 \tag{8}$$

Therefore, the intrinsic crack growth rate in weld metal is:

$$\left(\frac{da}{dN}\right)_{int} = \left(\frac{da}{dN}\right)_b + \Delta_2 \tag{9}$$

Fig. 1 shows schematically the changes in FCGR consisting of the increment Δ_1 arising from residual stresses and Δ_2 due to weld material property change. These increments, Δ, Δ_1 and Δ_2, can be either positive or negative and may not always be the same with the increase of ΔK.