BACK TO BASICS FOR THE FATIGUE CRACK GROWTH RATE IN METALLIC ALLOYS

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Abstract
The field of fracture mechanics started with Griffith's energy concept for brittle fracture in 1920. In 1963, Paris *et al*. used a fracture mechanics' parameter to introduce an equation for the fatigue crack growth rate in ductile materials and this equation is now commonly known as the 'Paris law'. However, the Paris law and the semi-empirical models that followed ever since do not fully account for the main intrinsic and extrinsic properties involved with fatigue crack growth in metallic alloys. In contrast, here we introduce a dimensionally correct fatigue crack growth rate (FCGR) equation that is based on the original crack driving force as introduced by Griffith and the presence of plasticity in a metal to withstand crack propagation. In particular we found that the FCGR shows a power law relationship with the cyclic strain energy release rate over the maximum stress intensity factor.

1. Introduction

Fatigue crack growth depends on specific aircraft usage and the predictive capabilities of the current crack growth models for variable amplitude loading are inadequate due to the aforementioned limitations of the Paris law and other semi-empirical models. This confines the aircraft operation to the usage spectrum that was applied during the full scale fatigue test of the aircraft. Here a dimensionally correct crack growth rate equation for tension-tension fatigue is introduced that accounts for the main intrinsic and extrinsic properties involved with fatigue crack growth in ductile materials. It will be shown that the new description intentionally corrects for the ratio between the minimum and maximum stress in a cycle during constant amplitude loading and for crack growth retardation under variable amplitude loading.

2. Results

Frost and Greenan and, independently, Pearson showed for a stress ratio (R) of almost equal to zero that the crack growth rates for materials with different Young's moduli merge onto a single curve when the main factor governing the crack growth rate is the concentration of elastic strain at the crack tip [1,2],, i.e.

$$\frac{da}{dN} = C\left(\frac{K_{max}}{E}\right)^n = C\left(\frac{K_{max}}{K_{max}}\frac{K_{max}}{E}\right)^n = C\left(\frac{G_{max}}{K_{max}}\right)^n \quad (1)$$

To account for different cyclic strain energy release rate at different stress ratios, Eq. (1) is adjusted in:

$$\frac{da}{dN} = C\left(\frac{\Delta G}{K_{max}}\right)^n = C\left(\frac{(1-R^2)K_{max}}{E}\right)^n \quad \text{for } R \geq 0 \quad (2)$$

where $\Delta G/K_{max}$ is the new parameter of similitude and ΔG can be regarded as the fatigue crack driving force and the inverse of K_{max} can be related to the presence of plasticity. The Young's modulus (E) was introduced empirically by Frost & Greenan and Pearson in Eq. (1), but in Eq. (2) it originates from ΔG. If $\Delta G/K_{max}$ is the new parameter of similitude, than any change in the maximum and/or minimum stress should result in a change in crack length at which a specific FCGR occurs:

$$\frac{1}{\beta(a)\sqrt{\pi a}} = \frac{constant}{S_{max}} \cdot \Delta U' \quad (3)$$

Eq. (3) indicates that if $\Delta G/K_{max}$ is the correct parameter of similitude the inverse square root of the crack length at a given FCGR and S_{max} should be proportional to the cyclic strain energy density ($\Delta U'$). For a given S_{max}, the $\Delta U'$ can be varied by varying the minimum stress. The linearity in both Fig. 1a and 1b is evidence that the parameter of similitude consists of two separate parameters, i.e. ΔG and K_{max}.

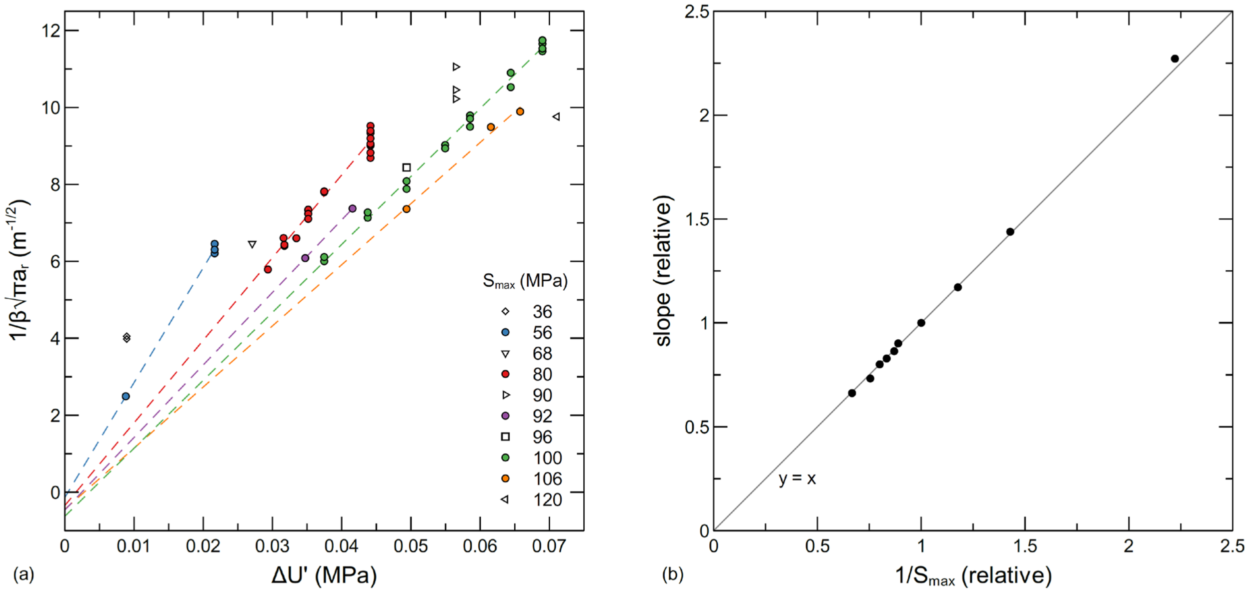

Fig. 1 (a) Inverse crack length term at 6.18·10^{-8} m/cycle as a function of $\Delta U'$ for different S_{max}. (b) Relative slope in (a) as a function of the relative inverse S_{max}. The slope and maximum stress of the 80 MPa fit was used as a reference

3. Conclusions

The new description is based on the orginal crack driving force as proposed by Griffith and corrects for the ratio between the minimum and maximum stress during a loading cycle at constant amplitude and for crack growth retardation under variable amplitude (VA) loading. It is shown that the outcome of this study allows for reliable predictions of VA fatigue crack growth life in aerospace structures as demonstrated in an international challenge, where the current theory prediction (submission 1) gave the best prediction compared to other state-of-the-art methods [3].

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