



Contents lists available at ScienceDirect

International Journal of Fatigue

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

From NASGRO to fractals: Representing crack growth in metals

R. Jones^a, F. Chen^a, S. Pitt^a, M. Paggi^{b,*}, A. Carpinteri^c^a Centre of Expertise in Structural Mechanics, Department of Mechanical and Aerospace Engineering, Monash University, Clayton, Victoria 3800, Australia^b IMT Institute for Advanced Studies Lucca, Piazza San Francesco 19, 55100 Lucca, Italy^c Department of Structural, Geotechnical and Building Engineering, Politecnico di Torino, C.so Duca degli Abruzzi 24, 10129 Torino, Italy

ARTICLE INFO

Article history:

Received 9 June 2015

Received in revised form 7 September 2015

Accepted 10 September 2015

Available online xxxx

Keywords:

Fatigue crack growth models

Fractality

Fatigue experiments

Profilometric analysis

Roughness

ABSTRACT

This paper presents the results of an extensive experimental analysis of the fractal properties of fatigue crack rough surfaces. The analysis of the power-spectral density functions of profilometric traces shows a predominance of the box fractal dimension $D = 1.2$. This result leads to a particularization of the fatigue crack growth equation based on fractality proposed by the last two authors which is very close to the generalized Frost–Dugdale equation proposed by the first three authors. The two approaches, albeit based on different initial modelling assumptions, are both very effective in predicting the crack growth rate of short cracks.

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1. Introduction

The breakdown of physical similitude in fatigue crack growth has been pioneeringly revealed in the early work of Barenblatt and Botvina [1]. Since then, several attempts have been made in order to understand the impact of this incomplete similarity on the Paris and Wöhler representations of fatigue. Experimental confirmation of size-scale effects has been reported by Ritchie [2] and generalized theories of fatigue based on dimensional analysis and incomplete similarity have been proposed [3–6] to interpret this anomalous phenomenon. Using these concepts, a dependency of the Paris' law on the grain size has also been put into evidence by Plekhov et al. [7].

Supported by these dimensional analysis considerations, a new fatigue crack growth theory based on fractality of crack profiles has been developed [3,6,8–12] to interpret the (experimentally evidenced) anomalous crack growth rate of short cracks and crack-size effects on the fatigue threshold, facts that were not fully explained by previous theories. At the same time and independently, Jones and coworkers [13–17] have shown that the anomalous crack growth rate of short cracks can also be captured using a generalization of the pioneering Frost–Dugdale equation [18]. It has also been shown [19] that the NASGRO crack growth equation with the constants determined from tests on long cracks can be

used to represent the growth of short cracks if closure effects are set to near zero and the threshold is set to a very small value.

In the present contribution, an extensive experimental analysis of the fractal properties of fatigue crack rough surfaces is presented.

Given the fact proven in the previous publications that the generalized fatigue crack growth equation based on fractality [8] and the generalized Frost–Dugdale equation [14] are both viable methods to model and simulate the anomalous fatigue behaviour of short cracks, in this study we attempt at applying the two approaches to a set of experimental data whose fatigue curves are known and from which it is possible to compute the profile fractal dimension, a key parameter in the fractal model. Analysis of the power-spectral density functions of profilometric traces shows a predominance of the fractal dimension $D = 1.2$. This result leads to a particularization of the fatigue crack growth equation based on fractality which is very close to the generalized Frost–Dugdale equation, thus explaining why the two approaches, albeit based on different initial modelling assumptions, are both very effective in predicting the crack growth rate of short cracks. Finally, by analogy with the generalized Frost–Dugdale equation, a generalization of the fractal approach in case of crack closure is proposed.

2. Crack growth equations

The recent state-of-the-art review of fatigue crack growth and damage tolerance [19] revealed that the growth of both long and

* Corresponding author. Tel.: +39 0583 4326 604; fax: +39 0583 4326 565.

E-mail address: marco.paggi@imtlucca.it (M. Paggi).

short cracks could be represented by the NASGRO crack growth equation [20], viz:

$$da/dN = D \Delta K_{\text{eff}}^{(m-p)} (\Delta K_{\text{eff}} - \Delta K_{\text{eff,thr}})^p / (1 - K_{\text{max}}/A)^q \quad (1)$$

where D is a constant, ΔK_{eff} is an effective stress intensity factor and the terms ΔK_{thr} and A are best interpreted as parameters chosen so as to fit the measured da/dN versus ΔK data. The term ΔK_{eff} is generally expressed in the form

$$\Delta K_{\text{eff}} = K_{\text{max}} - K_{\text{op}} \quad (2)$$

where K_{op} is defined as the value of the stress intensity factor at which the crack first opens. A range of formulae for determining K_{op} have been suggested in the related literature. However, the most widely used formulae for K_{op} was proposed by Newman [21]. This formulation is used in the crack growth computer programs FASTRAN, NASGRO and AFGROW. It was also shown that, as first suggested by McEvily et al. [22], the crack opening stress intensity factor K_{op} decays to K_{min} as the crack length reduces. One way to achieve this is via the McEvily et al. [22] formulation:

$$\Delta K_{\text{op}} = (1 - e^{-\lambda a}) \Delta K_{\text{opl}} \quad (3)$$

where ΔK_{opl} is the long crack value of ΔK_{op} ($=K_{\text{op}} - K_{\text{min}}$) and λ is a material dependent constant.

Jones [19] and Jones et al. [23] have shown that crack growth in a large cross-section of aerospace and rail materials can be captured by Eq. (1) with $m = p$ and $q = p/2$ and that in such cases p often takes a value that is approximately 2. Jones et al. [24] have also shown that this approach applies to Mode I, Mode II and Mixed Mode I/II disbonding in adhesively bonded structures.

On the other hand Jones et al. [13–17] have shown that the crack growth can also be captured using the Generalized Frost–Dugdale equation, viz:

$$da/dN = C^* a^{(1-\gamma/2)} (\Delta \kappa)^\gamma - (da/dN)_0 \quad (4)$$

where $\Delta \kappa$ is a crack driving force

$$\Delta \kappa = \Delta K^p (K_{\text{max}})^{(1-p)} \quad (5)$$

Here p , γ , which in most instances is approximately equal to 3, and C^* are constants, and the term $(da/dN)_0$ reflects both the fatigue threshold and the nature of the notch (defect/discontinuity) from which cracking initiates.

It was also shown that, in numerous instances, crack growth can be captured equally well by using Eqs. (1) or (4). Figs. 1–5 illustrate this by presenting crack growth data for 7050-T7451 and the MC and MB wheel steels replotted as per Eqs. (1) and (4). This phenomenon is also seen by comparing the crack growth representations presented in Jones et al. [25], which presents a crack growth data for a range of materials expressed as per Eq. (1), and by Jones et al. [17], which presents crack growth data for a range of materials expressed as per Eq. (4).

3. Fatigue crack growth of fractal cracks

Having established that the Generalized Frost–Dugdale equation and the Nasgro equation can effectively be used to describe the phenomenon of fatigue crack growth over a wide range of crack sizes, let us now examine the fractal representation of cracks. Let us consider a simple test such that the crack grows in pure Mode I, i.e. straight ahead, as per Fig. 6.

In this case the near tip stress field is proportional to $r^{-1/2}$, where r is the radial distance from the crack tip.

Now consider the case when the crack surface is rough and roughness is modelled as a fractal, as motivated by micromechanical considerations and molecular dynamics simulations, see Figs. 7 and 8.

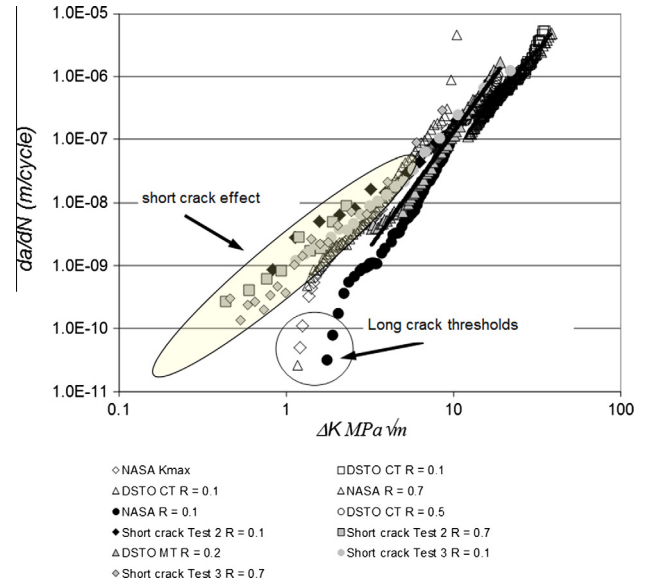


Fig. 1. Comparison of the various da/dN versus ΔK test data for AA7050-T7451, from Jones et al. [25].

In this case if the crack has a fractal dimension D ($1 < D < 2$), then the near crack-tip stress field takes the form [27–29]

$$\sigma \propto r^{(D-2)/2} \quad (6)$$

so that the nature of the near tip stress field is fundamentally changed and no longer has the classical linear elastic fracture mechanics (LEFM) $1/\sqrt{r}$ singularity.

The crack tip stress field only equates to the classical linear elastic fracture mechanics (LEFM) solution when the crack profile is a line in Euclidean space and thus has a fractal dimension $D = 1$. In all other cases the near tip stress field differs from the classical linear elastic fracture mechanics solution. In such cases, Spagnoli [3] and then Paggi and Carpinteri [8] have shown that crack growth depends both on the stress intensity factor K and the crack length viz:

$$da/dN = C^* / Da^{(1-D)(1+m/2)} (\Delta K)^m \quad (7)$$

where m and C^* are constants. This law is formally identical to the classical Paris law except that the coefficient multiplying the stress-intensity factor range is now dependent on the crack length a , whereas in the Paris law [30,31] it was assumed to be a material constant. At this stage it should be noted that Bouchaud [32] has shown that for small cracks the fractal dimension D is slightly varying and is about 1.2 in several natural examples. This finding was substantiated by Mandelbrot [33].

Frost and Dugdale [34] were the first to note that for many materials the crack growth rate is often (approximately) proportional to the cube of the stress amplitude $(\Delta \sigma)^3$. This has been confirmed by a range of investigations, viz: Frost et al. [35], Barter et al. [36], Molent et al. [37], Tsouvalis et al. [38], Jones et al. [17], and as a result is now adopted in the Royal Australian Air Force (RAAF) Structural Assessment Manual, Main [39], the RAAF P3C (Orion) repair assessment manual, Duthie and Matricciani [40] and Ayling et al. [41] and the Association of State Highway and Officials [42].

In addition to the assumption of cubic stress dependency, if we can also experimentally validate that D in Eq. (7) is approximately equal to 1.2, then Eq. (7) yields

$$da/dN = Ca^{-1/2} (\Delta K)^3 \quad (8)$$

which is a subset of the Generalized Frost–Dugdale equation, viz:

$$da/dN = C^* a^{-1/2} [\Delta K^p (K_{\text{max}})^{(1-p)}]^3 - (da/dN)_0 \quad (9)$$

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