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Prediction models of intrinsic fatigue threshold in metal alloys examined by experimental data

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ABSTRACT

A comprehensive study is carried out on the models for predicting the intrinsic threshold value for fatigue crack growth (FCG) in the absence of closure effects. The models reviewed and commented in this paper are based on different approaches, such as the models based on the mechanical properties of the materials and the so-called dislocations models. In particular, the model proposed for the first time in 1985 by one of the authors of the present paper, which is based on tensile and cyclic properties of the material, cyclic plastic zone size parameter and the minimum amount of physically possible crack advance (the inter-atomic spacing or Burgers vector) is revisited and compared with other models, through assessment of theoretically predicted values against more recent experimental data obtained in different types of metal alloys. It is shown that, once the appropriate material parameters are available, this model can give more accurate prediction results than other models.

1. Introduction

The fatigue crack growth threshold (fatigue threshold, in short) defines the stress intensity level where a crack will arrest or begin to propagate under service cyclic loading conditions [1]. In a similar way as the endurance limit is used in stress-life based design method, the fatigue threshold is used in the industry to define a durability lifetime (or safe operating time) for a component. Therefore, accurate threshold data is critical to the safety of damage tolerant based designs [2]. For design purposes, the lower-bound value for fatigue crack growth (FCG) in a given material at a certain microstructural condition, i.e. the concept of *FCG threshold*, ΔK_{th}, is probably much more important than the concept of fatigue/endurance limit (the stress amplitude, about zero mean stress, below which fracture does not occur, or occurs only after a very large number of cycles, $N_f > 10^7$ cycles). Threshold stress intensity range, ΔK_{th}, is the most widely used parameter to assess fatigue crack growth resistance.

For a given material (at a certain microstructural condition, and with a certain surface finish) the value of fatigue or endurance limit, herein denoted σ_e, is the result of a series of experiments carried out in order to obtain enough fatigue data to draw a Wöhler curve from which the value of σ_e is determined. The surface finish of the specimens used to determine the fatigue strength has a strong influence on the results because crack nucleation usually starts from incipient flaws or defects at the surface. Consequently, specimens with different roughness lead inevitably to different values of fatigue strength (or endurance limit).

On the contrary, for a given material at a certain microstructural condition, the concept of lower-bound value for FCG (ΔK_{th}) considers the presence of a crack of length *a*, which grows inside the material and therefore the value of ΔK_{th} is independent of the roughness of the outside surface of the specimen.

In the literature there are several papers dealing with the topic of near-threshold fatigue, modeling the crack growth behavior and calculating intrinsic threshold values, as for example references [3–7].

In addition to the intensive investigation on the fatigue threshold for long cracks, there are also many research works in the literature for studying the microstructural threshold for short cracks. Chowdhury et al. [8] proposed that there exist two different ΔK_{th} levels: (a) a microstructural threshold (for short cracks) and (b) a mechanical threshold (for longer cracks), which illustrates the distinction between the advancement of a short crack at microstructure level (characterized by fluctuating rate, when the crack is so small that its plastic zone is totally inside a grain) and stable propagation of a longer crack (in Paris regime) having a plastic zone that encloses several grains.

Riemelmoser et al. [9] gave one comprehensive review on the dislocation models for near threshold behavior of fatigue cracks in metallic systems. It was clearly explained why different simulation

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techniques are required to understand the different aspects of fatigue cracks, and what are the differences and similarities between the discrete dislocation modeling and the continuum plasticity models. For the macroscale plastic deformation in the upper Paris regime and above, the Finite Element Method (FEM) with continuum plasticity mechanics is appropriate; for the lower Paris regime, the mesoscale method is suitable; for the near threshold regime, the physical length scale is the Burgers vector of dislocations, so the dislocation models can be used to describe the near threshold plasticity. To answer the question where the plasticity comes from, i.e., where and when dislocations are generated, the molecular dynamic simulations are useful.

Due to limitations of measurement technique at the microstructural length scale, experimental characterization of micro-crack propagation remains a rather challenging task to-date [8]. However, as a short crack becomes progressively longer, the role of microstructural barriers diminishes until the crack grows sufficiently long to reach a stable propagation stage (the so-called stage II growth or Paris growth regime). The present paper is focused on the threshold for long cracks, which can be measured by experimental method and it is very important for evaluating the damage tolerance of the cracks detected by the non-destructive testing (NDT) methods applied to industrial structures.

The fatigue crack propagation rate at low stress intensity is very sensitive to microstructure, load ratio and environment. Test data of da/dN versus ΔK generally shows the significant effect of load ratio R on fatigue threshold behavior due to the crack closure effect. For most of the metallic systems, crack closure may be induced by plasticity, roughness and, mostly, by environmental/-corrosion attack.

Besides the test method using high stress ratios ($R \geqslant 0.7$) for measuring the closure free fatigue threshold, there are also some newly developed methods [10], e.g. compression precracking constant-amplitude (CPCA), compression precracking load-reduction (CPLR).

As it will be shown later on this article, there is a plateau or minimum value (denoted $\Delta K_{th,eff}$) independent of R, which can be considered the intrinsic threshold value for FCG in the absence of closure effects. In the literature this intrinsic threshold is also called effective or true threshold. Some researchers have suggested that the intrinsic threshold stress intensity under closure-free conditions, $\Delta K_{th,eff}$ (corresponding to ΔK_{th} at $R \geqslant R_{\mathrm{cl}}$, with $R_{\mathrm{cl}} = 0.7$ for many metal alloys tested in air) was a unique value for each alloy system, regardless of its metallurgical state [11].

Techniques for measurements of crack closure were summarized and discussed in the review work made by Lawson et al. [3]. In principle, compliance measurements of the specimen as a whole can diagnose the presence of closure. But, in reality, the variations in compliance are small and the measurements must be made near to the crack in order to show distinct changes. The analysis of a stiffness-load diagram using a COD gauge is the most common approach.

In the real situations there are many factors which affect fatigue thresholds [3,12–14]; for example: load ratio R, tensile strength or yield stress, microstructure, elastic modulus, environment, and so on.

James and Smith [15] presented experimental observations of the effect of crack size on ΔK_{th} at various positive stress ratios ($0.1 \leqslant R \leqslant 0.7$). The steel used was a 0.4% carbon EN8 designation steel in a quenched and tempered condition; the heat treatment adopted gave a microstructure consisting of finely dispersed carbides in a ferrite matrix. It was proposed that the observed anomalies in short crack behavior can be explained by using a crack closure argument. Kendall et al. [16] examined the behavior of physically short fatigue cracks in two structural steels and concluded that conservative life predictions may be based on a closure-free value of the threshold stress intensity range. The importance of residual stress fields surrounding the physically short cracks was emphasized. For long cracks, plasticity-induced closure in the wake of the growing crack influences the growth rates. Predictions of fatigue life using a closure-free value of the threshold were then recommended in applications in which reliance is placed on NDT control [16].

Comparison of crack growth behavior between typical "short crack" and "long crack" was clearly explained by James and Smith [15]. Later on, Chowdhury et al. [8] gave also a schematic demonstration, using a da/dN versus ΔK plot, of the crack growth regimes described by both conventional linear elastic fracture mechanics (LEFM) and microplasticity. The short crack effects observed at near threshold growth rates are primarily due to crack closure changes.

In this paper only the closure-free threshold will be studied, and attention will be paid to the effects influencing the closure-free threshold (also called intrinsic threshold). Firstly, a review is presented on the published models for prediction of the intrinsic fatigue threshold; and then, the experimental results of the threshold values for various materials are collected and comparisons are shown between the predicted results and the test values, which allows to draw conclusions about the validity or rationality of the models.

2. Threshold prediction models

Many attempts were made to develop theoretical models to relate the threshold values to the material's mechanical properties (e.g., yield stress σ_y; ultimate tensile stress σ_{uts}; Young's modulus E; strain hardening exponent n; fracture toughness K_{Ic}) and to extrinsic factors (e.g., loading conditions, environment, specimen geometry). Taylor [11] reviewed several models and classified them into four classes:

(1) Energy based models (a Griffith-type energy balance).
(2) Crack tip opening displacement models (CTOD) in which crack extension was assumed to be proportional to CTOD.
(3) Dislocations dynamics models based on dislocation mobility in the region ahead of the crack tip.
(4) Low cycle fatigue (LCF) models based on the assumption that material in the plastic zone undergoes LCF process.

In 1985 a model [17–19] for prediction the closure-free fatigue threshold $\Delta K_{th,eff}$ was developed based on the work of Radon [20] for calculating the strain range $\Delta\varepsilon_x$ at the distance x from the crack tip in the crack propagation direction:

$$\Delta\varepsilon_x = 2\varepsilon_{yc}\left[\frac{(1-2v)^2\Delta K^2}{4(1+n')\pi\sigma_{yc}^2 x}\right]^{1/1+n'} \quad (1)$$

where ε_{yc} is the cyclic yield strain, σ_{yc} is the cyclic yield stress, n' is the cyclic strain hardening exponent and x is the distance ahead of the crack tip where a local stress increase should occur. Eq. (1) can also be written as:

$$\Delta\varepsilon_x = 2\varepsilon_{yc}\left[\alpha_c\frac{\Delta K^2}{\sigma_{yc}^2 x}\right]^{1/1+n'} \quad (2)$$

where α_c is the cyclic plastic zone size factor, which was defined in [20] as:

$$\alpha_c = \frac{(1-2v)^2}{4(1+n')\pi} \quad (3)$$

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