Theoretical and Applied Fracture Mechanics 83 (2016) 93–104

Contents lists available at ScienceDirect

Theoretical and Applied Fracture Mechanics

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

Fatigue crack growth in the micro to large scale of 7075-T6 Al sheets at different *R* ratios

K.K. Tang [a,*], F. Berto [b,c], H. Wu [a]

[a] School of Aerospace Engineering and Applied Mechanics, Tongji University, Shanghai 200092, China
[b] Department of Management and Engineering, University of Padua, Stradella San Nicola, 36100 Vicenza, Italy
[c] NTNU, Department of Engineering Design and Materials, Richard Birkelands vei 2b, 7491 Trondheim, Norway

ARTICLE INFO

Article history:
Available online 27 February 2016

Keywords:
Multiscale
7075-T6 Al sheet
TCL/FCL
Strain energy density
R ratio

ABSTRACT

Transitionalized crack length (TCL) is derived from energy density based ΔS (incremental strain energy density factor) model that is inherently multiscaling, which is in contrast to the fictitious crack length (FCL) generated from da/dN–ΔK (incremental stress intensity factor) model. By employing transitional functions (TFs), the effects of material, loading and geometry (MLG) are incorporated and reflected in the multiscale fatigue crack growth process of 7075-T6 Al sheets. The constant change of MLG in metal fatigue is necessitated by the effects of Non-equilibrium and non-homogeneity (NENH). Variation of *R* ratios leads to the change of TFs accordingly. Particularly discussed are the effects of TFs on the fatigue crack growth of 7075-T6 Al sheets. Results turn out that TCLs have a relatively better agreement with test data than FCLs. The proposed model can possibly offer a predictive calibration for the ΔK model.

1. Introduction

Fracture mechanics of metal fatigue has been researched for decades [1–3]. The maximum stress as well as the initial crack length is incorporated in earlier fatigue models, while experimental data are collected and presented in the form of *log*–*log* plots of range in stress intensity factor variation ΔK versus cyclic crack growth rate da/dN [3]. It is expected, that a straight line relationship appears on the *log*–*log* plot. Moreover, it is generally accepted that the slopes and *y*-intercepts generated from the curve fitting are restricted to specific material, loading and geometry. Nevertheless, crack length versus cycles or time can be easily achieved through mathematical integration of the two-parameter equation. The integrated curve can be divided into three regions, namely region I, II and III. They are, respectively, referred to the threshold regime, stable crack growth or Paris region and fast crack propagation, which is also reflected on the sigmoidal curve for the plot of $\log da/dN$ against $\log \Delta K$. It should be noticed that this approach is stipulated to region II while regions I and III are left out. Only the sable growth region II is considered in the two-parameter model that is limited to monoscale.

With the advent of improved experimental means, efforts have been particularly focused on the microstructural effects on the fatigue crack life of advanced engineering alloys. Intrinsic and extrinsic attributes of microstructure in fatigue crack formation is highlighted. Effects of heterogeneity at smaller scales is worth checking [4]. The roles of microstructural features such as grain size, texture, and porosity. in crack initiation further affects the general fatigue life [5]. In other words, the fatigue crack growth process, to say at the least, involves both macroscopic and microscopic scales. The ΔK-based model is formulated upon stress criterion represented by the stress intensity factor K (SIF) [6,7]. Its limitation on monoscale necessitates a multiscale fatigue crack growth to be developed.

Energy criterion provides a more flexible solution for fatigue damage description of materials and structures. The cyclic hysteresis energy and cyclic strain energy density (SED) are the two energy criteria that stand out. The former exerts a relatively clear physical explanation for material failure, a better sensitivity to small changes of the prediction parameter and a stable value during the whole life for fatigue life prediction [8,9]. By considering the anisotropic behavior of the individual grains, the hysteresis energy is adopted as a criterion to predict the fatigue crack initiation and propagation. The hysteresis energy criterion is combined with continuum damage modelling and therefore is able to investigate the behavior of materials under cyclic loading at the microstructural level [10]. This kind of numerical simulation [11] is de facto in the framework of continuum damage mechanics [12,13].

* Corresponding author. Tel./fax: +86 21 65982267.
E-mail address: kktang@tongji.edu.cn (K.K. Tang).

http://dx.doi.org/10.1016/j.tafmec.2016.02.009
0167-8442/

Nomenclature

a_{pi-na}	*pi–na* crack length
a_{na-mi}	*na–mi* crack length
a_{mi-ma}	*mi–ma* crack length
$a_{ma-large}$	*ma–large* crack length
da/dN	fatigue crack growth rate
B and m	empirical parameters for da/dN–ΔS model
C and n	empirical parameters for da/dN–ΔK model
CDF	crack driving force
COT	cross-over threshold
d_{ma} and d_{mi}	macro length and micro length
FCG	fatigue crack growth
FCL	fictitious crack length
k_{ma}	dimensional compatibility factor
kc	kilocycles
MLG	material, loading and geometry
N	fatigue cycles
NENH	non-equilibrium and non-homogeneity
R	load ratio
RSM	reference of measurement
SED	strain energy density
TCL	transitionalized crack length
TF	transitional function
ΔK	incremental stress intensity factor
ΔS	incremental strain energy density factor, incremental crack driving force
μ, σ, d	transitional functions for material, loading and geometry
μ_{ma} and μ_{mi}	macro stiffness and micro stiffness
σ_{ma} and σ_{mi}	macro stress and local restraining stress
σ_m	mean stress
σ_a	stress amplitude

SED criterion [1,14] is the alternative effective approach for fatigue assessment. It refers to the strain energy stored in a volume element ahead of a crack tip that is a quadratic form of stresses. The strain energy is stored either at the microscopic or macroscopic scales. The energy density factor S naturally can be treated as the released energy at the initiation of instability and serve a crack growth factor in fatigue. It is adaptable for multiscaling problems, and applied to the fatigue crack growth prediction of cracks and notches [15–19], metallic alloys [20,21], as well as the bridge structures [22,23]. A localized energy density zone is defined in [24] to describe the fatigue crack growth from a micro-flaw to macro-crack, and the defined zone enables the macro and micro effects to be incorporated in one model. Emphasized is that the assessment of the damage severity is explicitly expressed through crack growth, which is different from the damage parameter defined in continuum damage mechanics. Thus it is preferred in the present work.

On the basis of SED criterion, a multiscale fatigue crack growth model da/dN–ΔS is formulated in previous work [25–27]. Aeronautical material 2024-T3 Al sheets is employed to investigate the fatigue crack growth behaviors that ranging from micro to macro ranges. Also proposed are the concepts of transitionalized crack length (TCL), as well as the fictitious crack length (FCL). The transitional functions (TFs) are proved to play a substantial role in the model, and they correspond to material, loading and geometry effects, respectively. Nevertheless, variation of TFs still need to be further clarified in accordance with the change of R ratios in the fatigue test.

In this regard, the paper is focused on the effects of varying R ratios on fatigue behaviors of 7075-T6 Al sheets at certain scale ranges. The stress ratio R is defined as the ratio of minimum stress to maximum stress $R = \sigma_{\min}/\sigma_{\max}$. Its influence on fatigue crack growth (FCG) has been successively investigated [28–32]. These research at different stages offer approaches such as crack closure concept and driving force parameter to the load effects on FCG behaviors. It is commonly agreed that at higher R ratios, the FCG behaviors tend to be faster and especially more sensitive at fatigue threshold. In this paper, the main goal is to investigate the R ratios effect on TFs and further affect the FCG behaviors of 7075-T6 Al sheets.

2. Multiscale fatigue crack growth model

In this section, a multiscale fatigue crack growth model is formulated based on the SED criterion. The two parameter crack growth rate relation is reminiscent of the Paris model developed in early years. In what follows, scale segmentation is made such that fatigue analyses can be divided into different ranges referred to as picoscopic, nanoscopic, microscopic and macroscopic. Expressions of ΔS are established accordingly. Transitional functions are addressed to reflect the NENH effects in the process of material fatigue damage.

2.1. Scale segmentation and stress singularity representation

Segmentation of the SI system of measurement was decided on a consensus basis for the expediency of assigning units to stress and energy density like quantities. In this regard, scale ranges are segmented as *pico–nano*, *nano–micro*, *micro–macro* and *macro–large*. Different stress singularity representations were introduced to develop the multiscale material damage model [33,34]. Note that λ is the order of the singularity defined as $1/r^{\lambda}$ that becomes unbounded as $r \rightarrow 0$. The singular order in Table 1 was derived from the argument that anti-symmetry is inherent at microscale in contrast to symmetry at the macroscale. Emphasized is that the scale segmentation could be different for materials and structures. The present research is focused on the 7075-T6 Al sheets in which centimeters could be attributed to the range of macro–large.

Displayed in Fig. 1 is the multiscale hierarchy of materials and structures. The cracks are ranging from nano to macro. With the increase of length scales, the singular order decrease from the order of 1.0 to 0.5. It is prudent to consider these cracks at various scales to be nanochemical, microstructural and macromechanical, although under certain conditions, it might not be the case. Minor defects at nano scale are not new to engineers, thanks to the nanomaterials in aeronautical and space applications [35]. Microstructural defects at microscopic scale are basically less than millimeters. Grain boundaries defects are usually categorized in the range of nano–micro. Aircraft fuselage cracks are mostly in the micro–macro range. Under certain circumstance, these cracks could evolve into large crack which is visible to naked eyes.

Table 1
Scale segmentation and stress singular order λ.

Scale range	*pi–na*	*na–mi*	*mi–ma*	*ma–large*
Length (m)	10^{-12}–10^{-9}	10^{-9}–10^{-6}	10^{-6}–10^{-3}	10^{-3}
Singular order λ	1.00	0.75	0.5	0.5