International Journal of Fatigue 56 (2013) 86–94

Contents lists available at ScienceDirect

International Journal of Fatigue

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

Engineering definitions of small crack and long crack at fatigue limit under tensile mean stress and a prediction method for determining the fatigue limit of a cracked Mg alloy

Shigeru Hamada [a,b,*], Takuya Kinoshita [c], Kazunori Morishige [c], Komei Hayashi [c], Toshiyuki Ishina [c], Hiroshi Noguchi [a]

[a] Department of Mechanical Engineering, Faculty of Engineering, Kyushu University, 744 Moto-oka, Nishi-ku, Fukuoka 819-0395, Japan
[b] International Institute for Carbon Neutral Energy Research (WPI-I2CNER), Kyushu University, 744 Moto-oka, Nishi-ku, Fukuoka 819-0395, Japan
[c] Department of Mechanical Engineering, Graduate School of Engineering, Kyushu University, 744 Moto-oka, Nishi-ku, Fukuoka 819-0395, Japan

ARTICLE INFO

Article history:
Received 26 November 2012
Received in revised form 11 July 2013
Accepted 7 August 2013
Available online 17 August 2013

Keywords:
Fatigue limit
Small crack
Non-propagating crack
Small-scale yielding
Mean stress

ABSTRACT

A simple method was proposed for evaluating the influence of mean stress on the fatigue limit of a cracked specimen using engineering approximations. Three types of crack sizes were introduced for evaluation: an "extra small crack," a "small crack," and a "long crack". The threshold stress intensity factor range was shown for each size based on crack non-propagation behavior using physical foundations. The effect of mean stress on the fatigue limit of the cracked specimen was formulated, and fatigue tests were performed on a magnesium alloy to check the approximation errors, which were found to be almost within 10%. Furthermore, the small-long crack transition was characterized experimentally.

1. Introduction

Every structural material has flaws that act as cracks at the fatigue limit, and every structural material is used under some mean stress σ_m; specifically, tensile σ_m reduces the fatigue limit [1]. Thus, the fatigue limit of structural materials with a crack under tensile σ_m must be evaluated. The modified Goodman diagram [1] is generally used to evaluate the fatigue limit influenced by σ_m; it is based on the theory that the fatigue limit decreases as the magnitude of tensile σ_m increases. This method is very useful because the influence of an arbitrary value of σ_m can be evaluated by the fatigue limit under a particular condition and tensile strength.

However, the fatigue limit of materials with a crack does not decrease according to the magnitude of the tensile σ_m and studies have reported that evaluations using the modified Goodman diagram may not provide accurate or suitable results [2,3]. Therefore, when evaluating the fatigue limit influenced by σ_m, the fatigue limit under every σ_m condition must be obtained, which means that a very large number of fatigue tests must be carried out. Moreover, the influence of the crack size on the fatigue strength—i.e., the small crack problem [4–9]—must be considered for a materials with a crack. The influence of the crack size does not need to be considered for a long cracks [8] to which linear fracture mechanics can be applied; however, the influence does need to be considered for a small crack [8]. Therefore, a great number of fatigue tests using various crack sizes are required to evaluate the influence of an arbitrary σ_m on a small crack of arbitrary size. This study proposes a simple method to evaluate the influence of σ_m on the fatigue limit of a cracked specimen based on the crack's non-propagation behavior using physical foundations.

A small crack has a different effect on fatigue strength compared to a long crack. Murakami et al. proposed the ΔK_{th} prediction equation for small cracks, which is valid for materials where $\sqrt{area} < 1000\ \mu m$ [2,10,11]. In this study, $\sqrt{area}$ is the square root of the projected area of a flaw in the direction of the load, and ΔK_{th} is the threshold stress intensity factor range. Murakami et al. drilled small artificial holes to serve as flaws, showed that a small crack and a small artificial hole are the same for ΔK_{th}, and concluded that their proposed prediction equation can predict the ΔK_{th} within a 20% error [2,11]. However, the value of $\sqrt{area} < 1000\ \mu m$ was obtained from fatigue test data on some carbon steels [2,11]; thus, its applicability to other metals is uncertain. Fig. 1 shows the relationship between ΔK_{th} and $\sqrt{area}$ for

* Corresponding author at: Department of Mechanical Engineering, Faculty of Engineering, Kyushu University, 744 Moto-oka, Nishi-ku, Fukuoka 819-0395, Japan. Tel.: +81 92 8023061; fax: +81 92 8020001.

E-mail address: hamada@mech.kyushu-u.ac.jp (S. Hamada).

0142-1123/$ - see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.ijfatigue.2013.08.006

Nomenclature

$2a$	surface length of pre-crack
E	Young's modulus
da/dN	fatigue crack propagation rate
HV	Vickers hardness
J	scalar amplitude of crack tip stress and strain field under nonlinear elastic conditions
ΔJ	cyclic component of J
ΔK	stress intensity factor range
ΔK_{eff}	effective stress intensity factor range
ΔK_{th}	threshold stress intensity factor range
$\Delta K_{\mathrm{eff,th}}$	threshold effective stress intensity factor range
$\Delta K_{\mathrm{th},R=-1}$	threshold stress intensity factor range at $R = -1$
$K_{\max}$	maximum applied stress intensity factor
$K_{\min}$	minimum applied stress intensity factor
K_{Imax}	maximum value of Mode I stress intensity factor
K_{op}	crack opening stress intensity factor
$K_{\mathrm{op,th}}$	threshold crack opening stress intensity factor
$\Delta K_{\mathrm{op,th},R=-1}$	threshold crack opening stress intensity factor range at $R = -1$
ΔP	applied load range
R	stress ratio
ε_f	elongation after fracture
γ	exponent value that characterizes effect of mean stress
$\Delta\sigma$	applied stress range
σ_0	uniform remote tensile stress
σ_m	mean stress
$\sigma_{\max}$	maximum applied stress
$\sigma_{\min}$	minimum applied stress
σ_w	fatigue limit
σ'_w	fatigue limit with mean stress close to zero
σ''_w	fatigue limit with high mean stress
$\sigma_{w,\mathrm{app}}$	approximated fatigue limit
$\sigma_{w,\mathrm{exact}}$	exact fatigue limit
$\sigma_{w,R=-1}$	fatigue limit at zero mean stress (for $R = -1$)
$\sigma_{\mathrm{eff,th}}$	fatigue limit for cracked specimen at $\Delta K_{\mathrm{eff,th}}$ condition
σ_{ut}	tensile strength
σ_Y	yield strength
$\sqrt{area}$	square root of projected area of flaw in direction of load

annealed 0.35% carbon steel [12–14], which was determined from the fatigue limits; the initial crack sizes were estimated from either the notch depth or grain size [14]. As shown in Fig. 1, if a crack is larger than a particular size, ΔK_{th} has a constant value irrespective of the crack size; if a crack is smaller than a particular size, ΔK_{th} shows crack-size dependence [4–9] depending on the material. The former is called a long crack, and the latter is called a small crack [8]. For small cracks, Murakami et al. proposed the relationship between ΔK_{th} and $\sqrt{area}$ as being $\Delta K_{th} \propto (\sqrt{area})^{1/3}$ [2,11]; however, the range of application of this formulation has not been clarified. The material and σ_m must be considered because the applicable range depends on the small-scale yielding (SSY) condition [8].

The definition of the small crack depends on the evaluation parameter. In this study, the small crack was defined using ΔK as the evaluation parameter; when ΔK is used, there exists an applicability limit, that is defined by small-scale yielding (SSY) hypothesis [15]. The existence of SSY has not been proven, however it can be used as an approximation [16]. Meanwhile, if the elastic–plastic

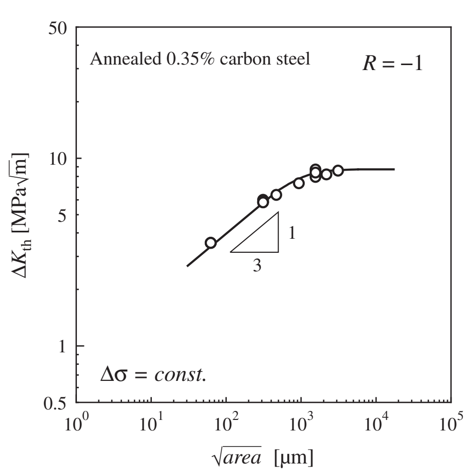

Fig. 1. Relaionship between threshold stress intensity factor range (ΔK_{th}) and square root of projected area of flaw in direction of load ($\sqrt{area}$) for annealed 0.35% carbon steel [12–14].

fracture mechanics (EPFM) approach is used, for example, using parameter J [17], the SSY problem can be avoided. However, J depends on the material characteristics; therefore, J-analysis is needed to evaluate in each material. On the other hand, ΔK does not depend on the material characteristics. Some methods have been proposed for evaluating fatigue crack propagation by using the J-integral for cyclic loading, that is, by using parameter ΔJ [18–20]. The applicability of ΔJ to evaluation of the fatigue crack propagation was shown empirically [21–23]; however, the universality of ΔJ has not been clarified, and the physical significance of ΔJ is still unclear [24]. Therefore, ΔK was used as the evaluation parameter in the present study.

This paper presents a simple method for evaluating the influence of mean stress on the fatigue limit of a cracked specimen using engineering approximations; fatigue tests were performed on a magnesium alloy to check the approximation errors.

2. Engineering definitions of small crack and long crack at fatigue limit under tensile mean stress

As the domain of a small crack at the fatigue limit depends on the SSY condition, there is no clear boundary for a small crack—that is, there is no scientifically defined boundary for a small crack. Thus, we first propose three domain concepts: the "extra small crack" domain, the "small crack" domain, and the "long crack" domain. These are defined under zero mean stress using the fracture mechanics pertinent to the relationship between ΔK_{th} and $\sqrt{area}$. We then introduce engineering definitions of three straight-line approximations. Fig. 2 shows the approximated relationship between ΔK_{th} and $\sqrt{area}$. In this study, a small crack was defined as one whose ΔK_{th} depended on the crack size; a long crack is larger than a small crack, and an extra small crack is smaller than a small crack. Fig. 2 outlines the dependence of ΔK_{th} on the crack size when the stress ratio (R) is equal to -1.

ΔK_{th} generally corresponds to the value when the fatigue crack propagation rate (da/dN) becomes zero as the stress intensity factor range (ΔK) of a compact tension (CT) specimen is decreased [25]; that is, the aand that of magnesium alloy isplied load range (ΔP) is decreased during the test. In this study, the ΔK_{th} value was calculated from the fatigue limit of a material with a cracked round