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Generation and analysis of FCG data using a single specimen and K_{max}–ΔK testing matrix

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ABSTRACT

A custom method to generate fatigue crack growth (FCG) data requires testing of multiple specimens at different load ratios, *R*, and the application of a load shedding procedure from pre-cracking level to threshold. In this paper, a novel method of testing has been investigated which utilizing a single specimen and a testing matrix in terms of K_{max} and ΔK values corresponding to predetermined *R*-ratios for which FCG data are recorded. Automatic *K*-controlled tests on 2324-T39 Al alloy were conducted using both increasing and decreasing ΔK procedures while K_{max} was kept constant. Results show that the increasing ΔK procedure gives less scatter than decreasing ΔK procedure. Also, fatigue crack growth curves near the threshold region obtained from increasing ΔK are above the curves obtained from decreasing ΔK procedure. These differences are explained by means of interaction between cyclic plastic zones and their effect on fatigue damage. The procedure with increasing ΔK demonstrated minimal interaction effects and hence it is recommended for efficient FCG data generation. The proposed procedure reduces testing time, the overall scatter associated with multiple samples and eliminates possible uncertainty linked to the load shedding procedure and its effects on threshold.

1. Introduction

Fatigue crack growth rate is governed by the loading variables such as stress intensity factor range, ΔK, maximum stress intensity, K_{max}, and stress ratio $R = K_{min}/K_{max}$ [1–3]. These variables are interrelated according to Eq. (1). Specifying any two variables is sufficient to define the loading conditions.

$$\Delta K = K_{max}(1 - R) \tag{1}$$

In general, fatigue crack growth rate, da/dN, may be expressed as a function of stress intensity factor range, ΔK, for a given stress ratio, *R*. Each curve characterizes a material's resistance to stable crack extension under a specific environment. It is a common practice to express fatigue crack growth rate using the Paris equation [4].

$$\frac{da}{dN} = C(\Delta K)^m \tag{2}$$

In the past, a number of empirical and semi-empirical models have been proposed in order to account for the *R*-ratio dependence on the da/dN vs. ΔK curves [5–10].

ASTM standard E647-05 describes test procedures to generate fatigue crack growth (FCG) rate data. First a cyclic tension–tension pre-cracking is applied. This is followed by force shedding (*K*-decreasing procedure) to obtain threshold. Then, *K*-increasing procedure is followed at a given constant load ratio, *R*. Fig. 1 depicts schematic of an *R*-constant testing with tension–tension pre-cracking shown from 0 to 1 followed by *K*-decreasing procedure from 1 to 2 continued by *K*-increasing procedure from 2 to 3.

Load shedding procedure results in obtaining threshold in terms of da/dN, usually 10^{-10} or 10^{-11} m/cycle. In this procedure stress ratio *R* is kept constant while K_{max} and K_{min} are decreased continuously. This is done by shedding force either in steps at selected crack extension intervals or in a continuous manner by an automated technique using a computer.

In Fig. 2 curve 1–2 represents data obtained from load shedding (*K*-decreasing procedure) and curve 2–3 represents data obtained from the *K*-increasing procedure. The fatigue crack growth rate curve from 2 to 3, as shown in Fig. 2, can be divided into three regions: near threshold (low crack growth rate), the linear region (the Paris region) and the quasi-static fracture region (high crack growth rate) [1–3].

In general, the *R*-constant testing requires one specimen for each stress ratio, resulting in testing multiple specimens in order to generate different stress ratios data. As each specimen is tested, it has to follow the above rather long and time consuming tension pre-cracking, force shedding and *K*-increasing procedure. Also, the threshold obtained from force shedding in case of *R*-constant testing may be affected by the rate at which force shedding is performed. Thus *R*-constant test may result in obtaining uncertain threshold values.

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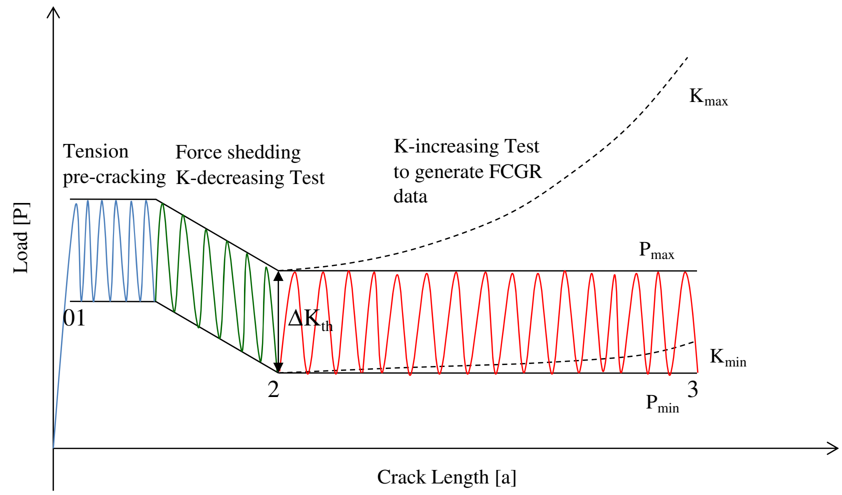

Fig. 1. Schematic showing R-constant testing according to ASTM standard E647-05.

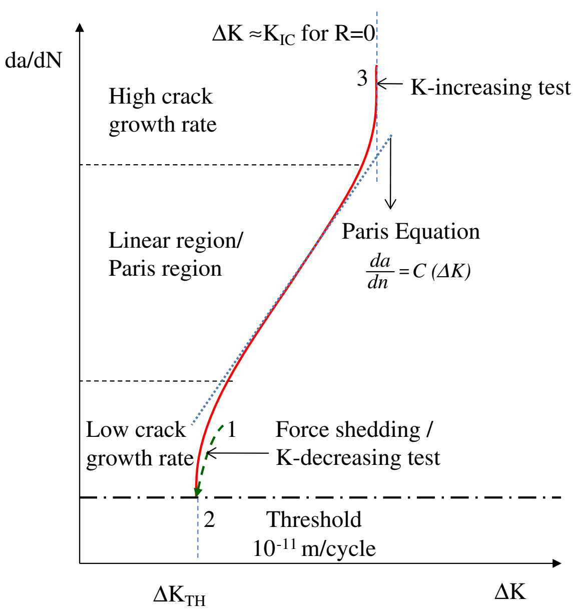

Fig. 2. A schematic of fatigue crack growth curve obtained from R-constant test.

Recently, Tesch et al. [11] proposed a new testing procedure to determine da/dN vs. ΔK curves using a single specimen. In this procedure K_{max} is kept constant while ΔK is decreased by gradually increasing K_{min}. As a result the stress ratio is not constant but increases continuously during the test. By successive application of stepwise increasing K_{max} procedure FCG data for a wide range of loading conditions can be generated. It is reported that the test data were acquired as da/dN–ΔK curves with varying R-values which are transformed into da/dN–ΔK curves with constant R-values. This transformation was reported to be in three stages and the detailed explanation of the transformation procedure can be found in Ref. [11]. This procedure is able to generate FCG curves for any stress ratio between $R = -1$ and 0.9 using one specimen with reduced testing time. However, FCG data for constant R-ratios must be derived using elaborated transformation and interpolation procedures.

In this paper, a new method to generate FCG data is being investigated which requires only one specimen and the data generated would not need any transformation or interpolation. The proposed method is based on a two-parameter driving force approach [12–16] which utilizes a testing matrix in terms of K_{max} and ΔK values corresponding to predetermined R-ratios for which FCG data are recorded.

2. A new single specimen procedure

The proposed procedure involves series of K_{max} constant tests within each ΔK is changed according to the predetermined testing matrix. The testing matrix gives the advantage of testing only K_{max} and ΔK values that are needed to generate the FCG curves instead continuously decrease ΔK proposed in Ref. [11]. In contrast to the ASTM procedure (R-constant test) where K_{max} is changed continuously, the advantage of keeping K_{max} constant is that the magnitude of the monotonic plastic zone in front of the crack tip is maintained constant. Hence, this method gives the flexibility of changing ΔK in large steps. Also, as only one specimen is needed to generate the FCG data for different R-ratios, testing time is reduced significantly. In this procedure ΔK is defined as $K_{max} - K_{min}$ for all R-ratios. This gives the advantage of having FCG curves widely spaced for the negative stress ratios [11]. The specimen is pre-cracked under compression–compression loading. A tensile residual stress left in front of the crack tip (due to compression–compression pre-cracking) and its effect is minimized by an additional crack extension of Δa_i under positive loading with K_{max} less than the initial K_{max} of the testing matrix as shown in Fig. 3. After pre-cracking is completed, a series of K_{max} constant tests are performed where ΔK is either decreased or increased in steps. In both ΔK increasing and ΔK decreasing procedures each ΔK value is applied for a predetermined crack extension of Δa. Data are recorded and the next ΔK value from the testing matrix is applied. Same procedure is repeated for all the K_{max} values in the matrix. Both, increasing ΔK and decreasing ΔK procedures are explained in the next section.

2.1. Determination of K_{max}–ΔK testing matrix

The testing matrix consists of ΔK values of predetermined stress ratios for the desired/chosen K_{max}. In order to construct the testing matrix, limits are set on the K_{max}, ΔK and R so as to confine the testing matrix to ΔK values needed to generate the FCG data for predetermined stress ratios. The limits for ΔK and K_{max} are chosen based on approximate values for K_{IC} and ΔK^{*}_{TH} as illustrated in Fig. 4 (where ΔK^{*}_{TH} corresponds to high R-ratio).