International Journal of Fatigue 102 (2017) 261–269

Contents lists available at ScienceDirect

International Journal of Fatigue

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

A universal functional for the physical description of fatigue crack growth in high-cycle and low-cycle fatigue conditions and in various specimen geometries

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A R T I C L E I N F O

Article history:
Received 8 November 2016
Received in revised form 30 January 2017
Accepted 31 January 2017
Available online 4 February 2017

Keywords:
Fatigue
Crack growth
High-cycle fatigue
Low-cycle fatigue
Aluminum
Titanium
Nickel
PMMA

A B S T R A C T

A simple universal functional is shown here to correlate fatigue crack growth data of a wide variety of materials (metals, polymers), test conditions (high-cycle and low-cycle fatigue), and specimen configurations (tension and bending). The proposed functional is a power law that relates the normalized remaining ligament size to the normalized remaining fatigue life in a cyclically loaded specimen. The functional evolved from the idea that at any stage during fatigue, the remaining fraction of cycles required to fracture the specimen, completely, depends on the remaining fraction of section to be broken by the fatigue crack before that final fracture. More importantly, the surrogate form of the functional is shown to provide excellent descriptions of the raw crack-length-versus-cycles data in fatigue crack growth. The functional provides a new physical basis to characterize fatigue crack growth in materials and is promising for extensions in to more complicated fatigue loading conditions.

1. Introduction

Fatigue failure of metals is caused by the nucleation of a microscopic crack and the subsequent propagation under cyclic loading, through the cross-section of the specimen or structure, until the final ligament breaks in the last cycle. Fatigue testing, in laboratory, is usually done under constant amplitudes of stress, which lies within the range of $\sigma_u > \sigma_a > \sigma_e$ (where σ_u, σ_a and σ_e are the ultimate tensile strength, fatigue stress amplitude and endurance limit stress, respectively). This testing is done to generate the complete stress-life (S-N) curve that characterizes the fatigue behavior of a material.

The author has previously hypothesized [1] that, at any stress amplitude between σ_u and σ_e, the number of cycles required to break the remaining specimen cross-section by fatigue is related to the size of that section. The basis for this hypothesis can be explained with the help of Fig. 1. At the highest possible stress amplitude, which is the ultimate tensile strength, the specimen fracture occurs in approximately one cycle. At stress amplitudes lower than this, but higher than the endurance limit stress (σ_e), the fatigue fracture can also be thought of as the monotonic fracture of the final remaining section in the last fatigue cycle. This is because the level of stress amplitude has reached the tensile strength level (or residual strength) of the remaining ligament at that point, as illustrated in Fig. 1. This situation occurs for all stress amplitude levels within the range of $\sigma_u > \sigma_a > \sigma_e$. Experimental data in literature [2,3] indeed show that the net section stress in the last fatigue cycle is approximately equal to the tensile strength of the material. Below the lowest possible stress amplitude, that is the endurance limit stress, either no fatigue crack is formed or only non-propagating cracks are found. Thus, it can be argued that, at stress amplitudes higher than σ_e, the role of fatigue crack growth in N_f-1 cycles is to reduce the size of the load-bearing section small enough to fracture it monotonically in the last fatigue cycle. At a relatively low stress level, but above σ_e, the fatigue crack has to sever through a relatively larger area fraction of the specimen section in order to increase the stress level in the final ligament to the level of the tensile strength. However, at a relatively high stress level, the crack needs to advance only a few cycles because the extent of crack growth, required to increase the ligament stress to the level of tensile strength, will be proportionately small. Hence, it can be expected that there should be a direct relationship between the fractional length of the unbroken section and the fractional cycles needed to reach the point of monotonic fracture of the final ligament.

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http://dx.doi.org/10.1016/j.ijfatigue.2017.01.046
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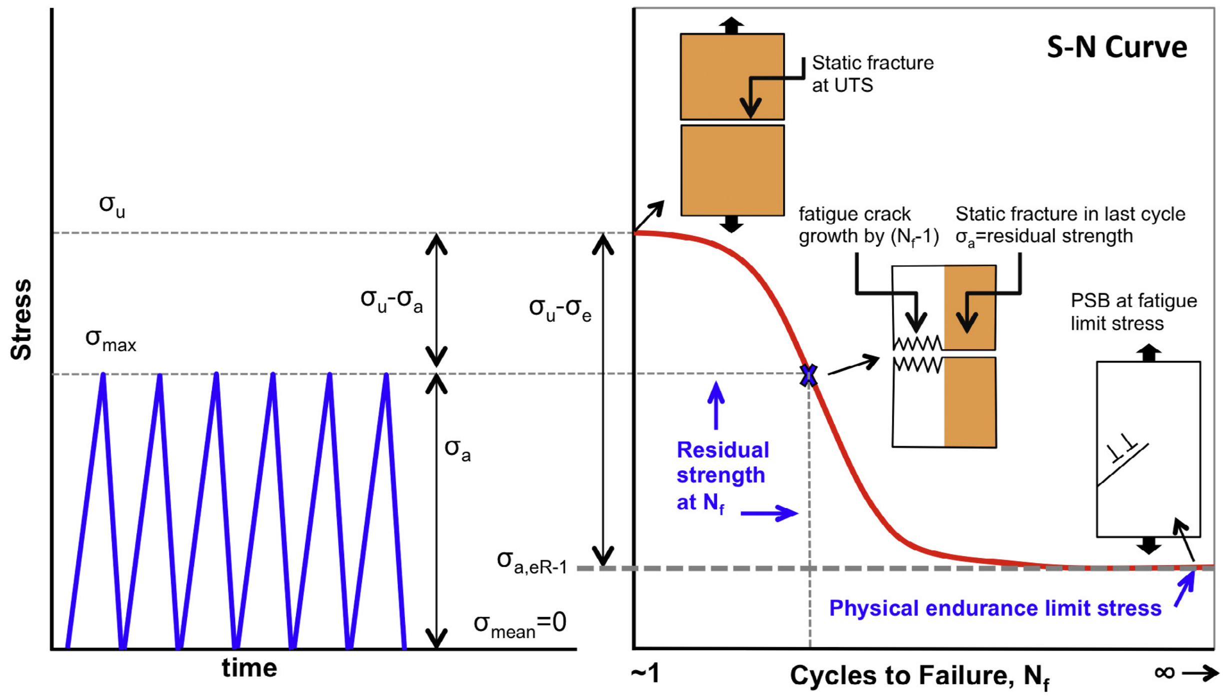

Fig. 1. Scaling of stress amplitude of a fatigue cycle between the ultimate tensile strength (σ_u) and the endurance stress limit (σ_e) of the material.

The objective of this work is to show that the proposed functional provides excellent correlations of fatigue crack growth data for a wide variety of materials, test conditions including high-cycle and low-cycle fatigue, and for different specimen geometries loaded in tension and bending. A surrogate function is then proposed to provide a physical description of fatigue crack growth (crack-length-versus-cycles or a-N data). This function is applicable to any specimen cross-section size.

2. The fatigue crack growth functional

The fatigue crack growth functional is given by Eq. (1) as follows:

$$\left\{1-\frac{a}{W}\right\}=\left\{1-\frac{N}{N_f}\right\}^k \tag{1}$$

where k is the constant characterizing the nature of crack growth, N is number of fatigue cycles corresponding to crack length, a, and W is the width of the specimen. For a given crack length, the parameter (1-N/N_f) is the remaining fraction of cycles that are required to growth that crack through the fractional remaining ligament, (1-a/W). Fig. 2 illustrates the fractional cracked and uncracked sections for center-cracked-tension (CCT), single-edge-notched-tension (SENT) and round-bar (RB) specimens. For round bar specimens used in axial or rotating bending fatigue, the normalized remaining section is defined as (1-2C/S) where 2C is the circumferential surface length of the crack and S is the circumference of the round specimen. The ratio of surface length to specimen circumference in round specimens was found [4] to be approximately equal to the ratio of the maximum crack depth to the specimen diameter and therefore (1-2C/S) is geometrically similar to (1-a/W).

It is important to note that the functional (Eq. (1)) assumes that the fatigue crack starts to grow from zero size at zero cycles, which implicitly suggests that the crack is ready to grow from the first cycle. This is the situation of the growth of an infinitesimally small crack (on the order of a burgers vector that defines the first slip step, at stresses >σ_e), through the small- and large-crack-growth regimes, that is captured by the functional. However, in many fatigue experiments crack growth data is obtained on cracks growing from pre-existing notches or holes. In fatigue of smooth specimens, however, a small crack naturally initiates at the surface, after some initial cycles, and grows to final failure. In both cases, there can be an incubation period (often referred to as the crack nucleation life) below which a fatigue crack either has not initiated or has not been experimentally detected. For these situations, either the initial notch size or the nucleated crack size, a_o, and the corresponding cycles for crack initiation, N_o, can be subtracted in the functional as follows:

$$\left\{1-\frac{a-a_o}{W}\right\}=\left\{1-\frac{N-N_o}{N_f-N_o}\right\}^k \tag{2}$$

In the examples presented in Section 4, it is shown that five different sets of fatigue crack growth data can be correlated extremely well by Eq. (1) for cracks growing from near-zero crack sizes. Five other sets of data, for cracks growing from preexisting notches, were found to be correlated equally well by Eq. (2). These evaluations will illustrate the excellent versatility of the functional.

3. Comparison with other relationships between normalized crack length and normalized fatigue life

It is relevant to mention here that there are some rudimentary approaches, relating the normalized crack length data to the normalized fatigue life, proposed in fatigue literature. Gallagher and Stalnaker [5], attempted to correlate the growth of fatigue cracks in aircraft components using normalized crack lengths and normalized fatigue life. They showed that fatigue crack growth data, obtained at different stresses of flight simulation loading, can be approximately consolidated into a single curve when the normalized crack size ((a-a_i)/(a_f-ai), where a is the crack length at N cycles, and a_i and a_f are the initial flaw size and the crack length at which final fracture occurs, respectively) is plotted as a function of the normalized fatigue life (N/N_f). This was done from the observation of the similarity between the growth behaviors of cracks in