GENERAL FEATURES OF FATIGUE FRACTURE DIAGRAMS OF METALS*

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In this paper the results of investigations of fatigue fracture diagrams (v-K diagrams) of materials or products (depicting the relationship between the fatigue crack growth rate, v, and stress intensity factor range in a cycle, AK) performed in the Physico-mechanical Institute are summarized. Typical diagrams are described and their main features in normalized coordinates are clearly demonstrated. On this basis the defining parameters of crack growth rate curves (v-K curves), AKth, Ky c, m, and AK*, characterizing the crack extension resistance of material are validated. Convenient expressions for analytical approximating v-K curves by splines are proposed. The main observed deviations of v-K curves from typical ones are shown.

Introduction

Feature of materials under long-term constant or alternate load (i.e., fatigue) belongs, as is known, to the most important problems of reliability and endurance of engineering structures. Therefore the methods and means of diagnostics and prediction of residual strength and fatigue crack life of materials under given service conditions present particular scientific and practical interest. The basis for such methods are fatigue fracture (or crack growth rate) diagrams which comprehensively display information about the fatigue crack extension resistance of materials (products) obtained from tests. The diagram (Fig. 1) shows in the form of a data point set the relationship between the fatigue crack growth rate (this is averaged crack extension, Aa, per load cycle under given test conditions), v = Δa/dN, and the mechanical state at the crack front. The latter is characterized in terms of a fracture parameter which is usually expressed by the maximum value of the stress intensity factor, Kmax, or, more frequently, stress intensity factor range, ΔK, in the cycle as a controlling factor, while other test parameters (load ratio R, frequency, form of cycle, etc.) are held constant. Hence these diagrams are hereafter called v-K diagrams. Such an approach ensures the uniqueness and reproducibility (within the natural data spread) under known conditions [1, 2], primarily when inelastic zones at the crack front are small as well as the time and history effects sufficiently weak.

Abstracting from data spread the crack growth rate as a function of ΔK (Kmax) can be represented by a regression curve of fatigue crack growth rate (hereafter referred to as the v-K curve) that fits to the points of the v-K diagram.

The Typical v-K Curve. The v-K curves of metallic materials in spite of different crystalline structures and microstructures, chemical and phase compositions, and dissimilar test conditions (normal and low temperatures, vacuum, air of different humidity, etc.) have common main features. The typical generalized v-K curve plotted in the V-AK or v-Kmax coordinate system with logarithmic scales on both axes (Fig. 1) as represented by an S-shaped curve which

- is on both sides limited by vertical asymptotes ΔK = Kth (Kmax = Kth) and ΔK = ΔKfc = (1 - R)Kfc (Kmax = Kfc);
- consists of the middle segment 2, closely approximated by a straight line between the points with abcissa AK1.2(K1.2) and two side curvilinear segments of low 1 (usually less than 5·10^-8 m/cycle) and high 3 (usually more than 5·10^-6 m/cycle) crack growth rate;
- is approximately symmetrical about its middle point with abcissa ΔK = (ΔKthΔKfc)^1/2 or Kmax = (KthKfc)^1/2.

These common features are clearly visible in the generalized diagram (Fig. 2), built in normalized coordinates.

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Fig. 1. The $v-K$ diagram. The $v-K$ curve is represented by the middle line while the dashed lines limit the data point scatter band. 1, 2, 3 are the regions of low, intermediate, and high fatigue crack growth rate, respectively, which correspond to the appropriate segments of the $v-K$ curve.

$$\xi = 2 \frac{\lg(\Delta K_{\text{max}}/\Delta K_{\text{th}})}{\lg(\Delta K_{\text{fc}}/\Delta K_{\text{th}})}, \quad \eta = \lg(v/v_S),$$  

where $v_S = v$ at $\Delta K = \Delta K_S$ and $\Delta K_S = (\Delta K_{\text{th}}\Delta K_{\text{fc}})^{1/2}$.

There are more than 500 points (a portion of the points are superimposed from 19 $v-K$ diagrams of different steels and aluminum alloys, tested at a stress ratio less than 0.1 and under different conditions (e.g., ambient and low temperature). All the represented experimental data remain in a relatively narrow scatter band, and hence, confirm strong correlation between $v$ and $\Delta K$ and general common features of the diagrams of various materials under different test conditions. On this basis characteristics of fatigue crack extension resistance are established by means of which the $v-K$ curve can be reproduced with reasonable accuracy, i.e., to the inherent scatter. The basic characteristics are: fatigue crack growth threshold, $\Delta K_{\text{th}}$; fatigue fracture toughness, $K_{\text{fc}}$; parameters of the equation of the rectilinear middle segment of the $v-K$ curve.

**Analytical Expressions for the Description of the $v-K$ Curves.** Many analytical expressions were proposed. Their review is given in [3, 4]. In most cases, the parameters in these expressions do not have a clear physical sense and, thus, cannot be considered as characteristics of the crack extension resistance of the material. Among them the expression proposed by Yarema and Mykytshyn

$$v = v_0 \left( \frac{K_{\text{max}} - K_{\text{th}}}{K_{\text{fc}} - K_{\text{max}}} \right)^q$$  

has some advantages [1].

Here, besides $K_{\text{th}}$ and $K_{\text{fc}}$, there are two parameters; $v_0$ is the crack growth rate at the middle point of the diagram $K_{\text{max}} = (K_{\text{th}} + K_{\text{fc}})/2$ and exponent $q$. Using the parameters $q$ and $v_0$ the values of independent parameters $K^*(\Delta K^*)$ and $m$ in the modified Paris equation

$$v = v^* \left( \frac{\Delta K}{\Delta K^*} \right)^m = v^* \left( \frac{K_{\text{max}}}{K^*} \right)^m, \quad v^* = 10^{-7} \text{ m/cycle}.$$