TWO-PARAMETER APPROACH FOR SHORT CRACKS AT NOTCHES

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ABSTRACT

A two parameter constraint-based fracture mechanics method is applied to the behavior of microstructurally and mechanically short fatigue cracks. A short crack in the vicinity of a grain boundary and a crack which is engulfed by the plastic strain field of a notch are studied as examples. The different levels of stress constraint are quantified by using the T-stress and the Q parameter. The corresponding calculations are performed by using a finite element method (ANSYS system). The influence of the T values on the propagation of short fatigue cracks is analyzed. The size of the plastic zone and the crack closure are significantly affected by the level of constraint. The influence of constraint on small fatigue crack growth kinetic is studied under the assumption that the controlling variable for the rate of propagation of the fatigue crack is the size of the plastic zone.

KEYWORDS

Short fatigue cracks, notches, Q-parameter, finite element method

INTRODUCTION

Experimental data characterizing the growth of fatigue cracks on the basis of fracture mechanics are obtained from specimens containing relatively long cracks, typically tens of millimeters. Direct application of these laboratory data to the characterization of short fatigue cracks (ranging from a fraction of a millimeter up to 1 millimeter) is not acceptable and would lead to dangerous overestimation of the fatigue lives of many engineering components.

The usual classification of short fatigue cracks suggests the following types [8]:

(1) microstructurally short cracks, for which the crack size is comparable to a characteristic microstructural dimension such as the grain size,

(2) mechanically small cracks for which the near tip plasticity is comparable to the crack size,

(3) physically short cracks with lengths typically less than a millimeter,

(4) chemically short cracks, which exhibit anomalies as a consequence of environmental stress corrosion effects on crack dimensions.

The analysis and application of experimental data for short cracks can be difficult for several reasons. These include the failure of linear elastic fracture mechanics to adequately describe of the crack tip stress field, the irregular nature of many short cracks, and the influence of grain boundaries. As a result, the fatigue crack growth threshold for short cracks may be smaller than for long cracks and, generally, fatigue crack growth rates may be greater.

In the present contribution the first two types of short crack are analyzed from the point of view of two-parameter constraint based fracture mechanics. With this aim, the different levels of stress constraint due to the specimen geometry and the position and orientation of the short cracks are quantified by means of the T-stress and the Q parameter. The results can contribute to explanation of the differences in behavior between of short and long fatigue cracks.

TWO-PARAMETER FRACTURE MECHANICS

Two-parameter fracture mechanics provides a tool to account for the differences in constraint on the stress distribution around the tip of a crack. In the framework of linear-elastic fracture mechanics, the influence of constraint is described by mainly using the T-stress (or, equivalently, the biaxial parameter B). The T-stress denotes a constant-stress term acting parallel to the crack flanks [1] and is related to the second term in the Williams expansion of the stress field [9], i.e.,

$$\sigma_{ij} = \frac{A_1}{\sqrt{r}} f_{ij}^{(1)}(\theta) + A_2 f_{ij}^{(2)}(\theta) + A_3 \sqrt{r} f_{ij}^{(3)}(\theta) + \ldots, \quad (1)$$

where K_I is the corresponding stress intensity factor, and $f^{(k)}_{ij}$ is a function of the polar angle θ. The biaxiality parameter B is related to the T-stress by the relation [5]

$$T = \frac{BK_I}{\sqrt{\pi a}}, \quad (2)$$

where a is the corresponding crack length.

In elastic-plastic fracture mechanics, the parameter Q is used to characterize the constraint. According to, e.g., [1] Q is defined as follows:

$$Q = \frac{(\sigma_{yy}) - (\sigma_{yy})_{SSY,T=0}}{\sigma_0} \text{ at } \theta = 0 \text{ and } r\sigma_0 / J = 2, \quad (3)$$

where σ_{yy} is the value of the stress component calculated for the given configuration, $(\sigma_{yy})_{T=0}$ is the reference component of stress calculated under the assumption that T = 0 and for small scale yielding approximation, and σ_0 is the yield stress of the material. The value of $(\sigma_{yy})_{T=0}$ is usually estimated by the modified boundary layer method [1]. J is the corresponding value of the Rice integral.

Generally, the fracture toughness tends to increase as the constraint decreases (i.e., as T or Q becomes more negative).

Under well-contained yielding, T and Q are uniquely related [6]. The T-stress loses its meaning when significant yielding precedes fracture.

The influence of the T-stress on plastic zone size r_p and crack opening displacement δ_t can be described for plane strain yielding by the following expressions [3]

$$r_p = \frac{1}{18}\pi\left(\frac{K_I}{\sqrt{3}\tau_Y}\right)^2 \left[1 - \frac{4}{3}\sqrt{\frac{2}{3}}\left(\frac{T}{\sqrt{3}\tau_Y}\right) + \ldots\right], \quad (4a)$$

$$\delta_t = \frac{16}{27}\sqrt{\frac{2}{3}}\frac{\left(1-\nu^2\right)K_I^2}{E\left(\sqrt{3}\tau_Y\right)}\left[1-\frac{2}{3}\sqrt{\frac{2}{3}}\left(\frac{T}{\sqrt{3}\tau_Y}\right)+\ldots\right], \tag{4b}$$

where τ_y is the shear yield stress. The formulas (4) make it possible to estimate the deviation of the values of r_p and δ_t due to constraint from these values given by the one-parameter small scale yielding approximation. Generally, for the same level of the stress intensity factor K,

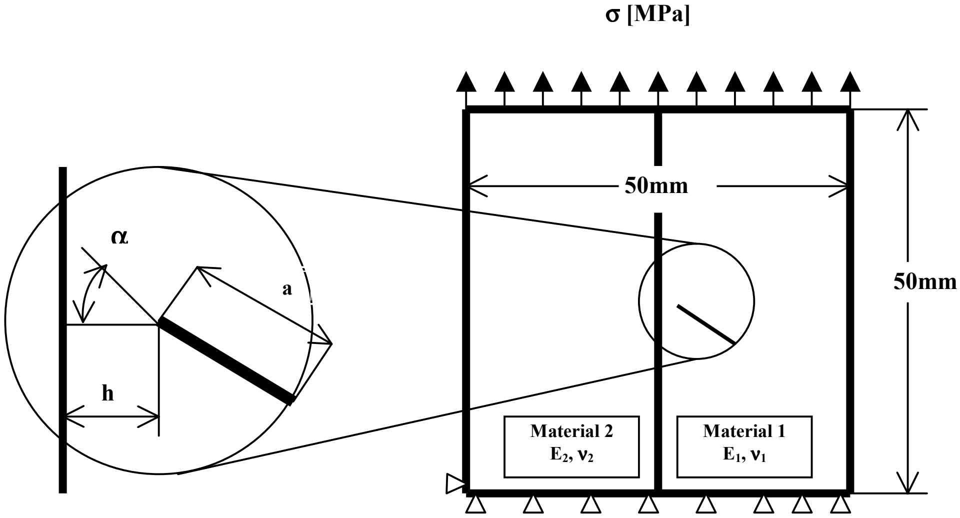

Fig.1. Numerical model of a microstructurally short crack near the grain boundary, see [7].

negative values of the T-stress strongly influence plastic zone size and the crack opening displacement The fatigue crack propagation rate increases with decreasing values of the T- stress.

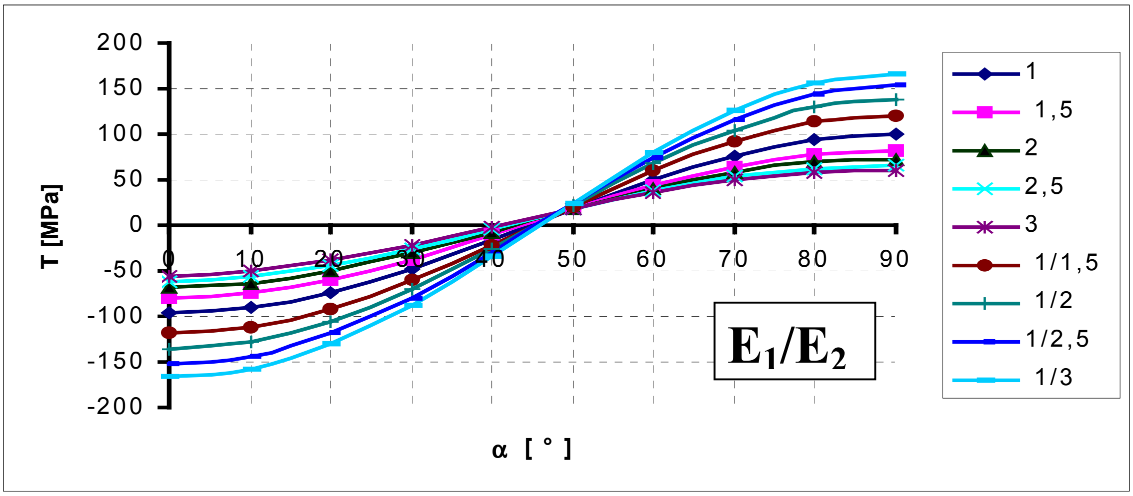

Fig.2. The dependence of the T-stress on the orientation of the short crack for different ratio of E_1/E_2 . The values of the T-stress becomes more negative for proper orientation of a crack with respect to the interface.

Depending on the value of the T-stress, differences in the crack propagation rate for the same value of K due to constraint may be as much as 100%.The quantitative relation between the T-stress values and the rate of a fatigue crack is given in [4].

In the next chapter, parameters T and Q are calculated for two types of short cracks.

NUMERICAL ANALYSIS AND RESULTS

Knowledge of the T-stress value is necessary to estimate the effect of microstructure on the behavior of short cracks. In the following, the influence of a grain boundary on the T-stress

value is estimated. The calculations have been performed by the finite element system ANSYS [2]. The numerical model used to evaluate the T-stress is shown in Fig.1.see

reference [7] for details. The grain boundary was modeled as an interface between two different elastic materials, and the T- stress was estimated as a function of the elastic material

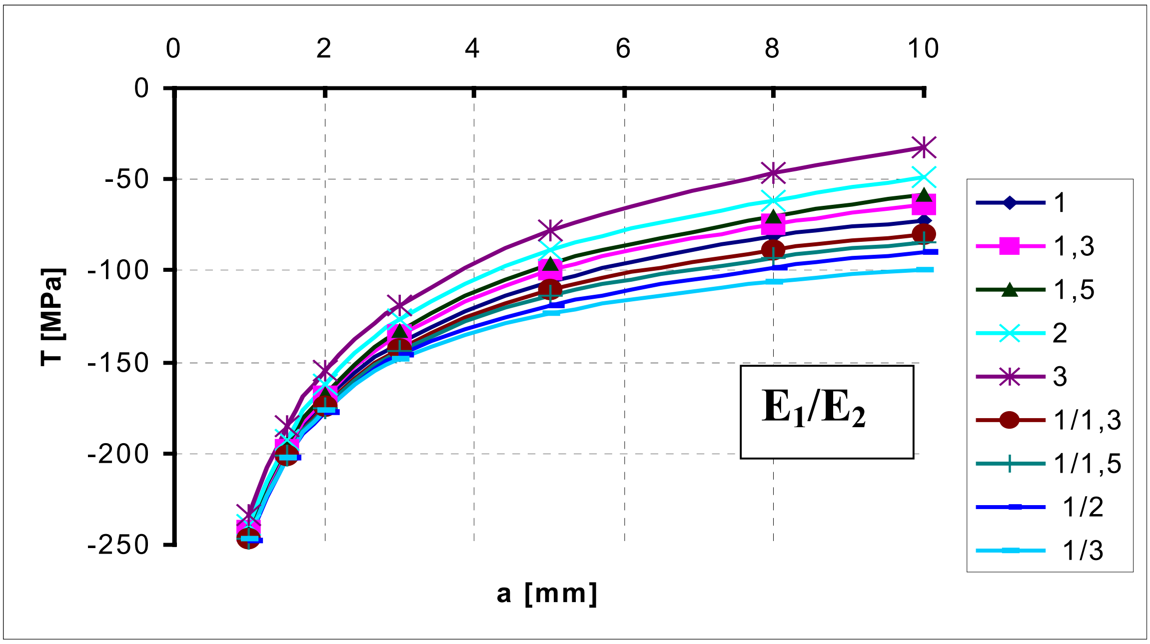

Fig.3. The calculated dependence of the T-stress on the length of a crack a . The T-stress value becomes more negative for short cracks.

parameters and the orientation of the crack with respect to the grain boundary, see Fig.2. The results of the calculations show that the T-stress strongly depends on the orientation of the short crack with respect to the grain size. Small cracks of microstructural size are more strongly affected by local stress field than longer cracks, see Fig.3. The existence of negative values of the T-stress influences plastic zone size and crack opening displacement, see Eq.(4). The crack propagation rate of properly oriented small cracks is greater than for longer cracks. This can be quantified by using the results of reference [6], where the fatigue crack propagation rate is related to the T-stress values for long fatigue cracks.

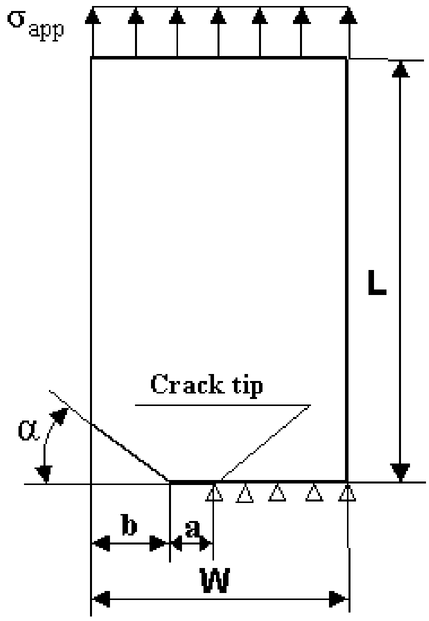

Fig.4. Numerical model of a mechanically short crack initiated at the tip of a V-notch.

Mechanically small cracks have been modeled as cracks initiated at and growing from the tip of a V-notch, see Fig.4. For a very short crack, a/b << 1 , where a is the length of the crack, b is the depth of the notch, see Fig.4., such a crack is engulfed by the plastic strain field of the notch, see Fig.5a. In this case the Q parameter must be calculated. An example of such analysis is shown in Fig.6., where the values of Q are calculated as a function of notch opening angle α and the ratio of a/b . On the other hand for "longer" short cracks, where a/b ~ 1, the crack tip is not engulfed by the plastic field of the notch and the T-stress is again sufficient to describe the influence of constraint on the short fatigue crack behavior see Fig.5b. The T-stress calculations for this case are presented in Fig.7. The calculations for both cases of mechanically short fatigue cracks, i.e. for a/b << 1 and a/b ~ 1, see Figs. 6 and 7, and the existence of a relationship between the T-stress and the Q parameter, see [6], indicate the possibility of a unified description of the influence of constraint on short fatigue crack propagation rate based on the T-stress. The negative values of the T-stress for short cracks initiated at the tip of a V-notch suggest an increase in the crack propagation rate due to constraint.

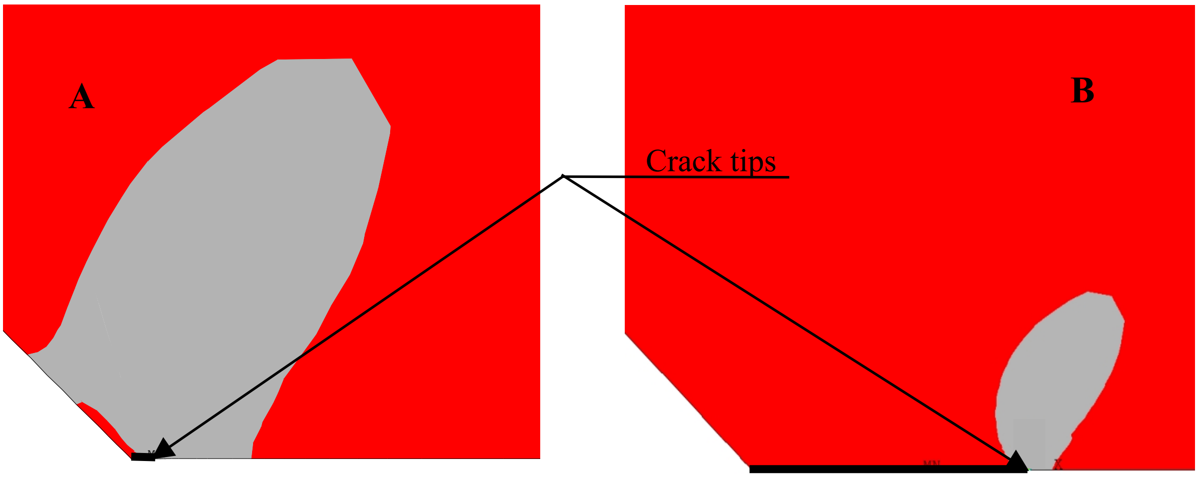

Fig.5-A. A mechanically short crack which is engulfed by the plastic zone of the V-notch. Case of the very short crack, where *a/b* << 1. The constraint is characterized by Q-parameter.

B. A mechanically short crack for *a/b* ~ 1. The crack tip is not engulfed by the plastic zone of the V-notch and to estimate the effect of the constraint on the behavior of the short fatigue crack the knowledge of T-stress is adequate.

CONCLUSIONS

A two-parameter fracture mechanics method has been applied to problems of the behavior of short fatigue cracks. Microstructurally and mechanically short cracks have been analyzed and the T-stress and Q- parameter have been calculated. It has been shown that in both cases the T-stress can be used to characterize the influence of constraint on the rate of propagation of a short fatigue crack.

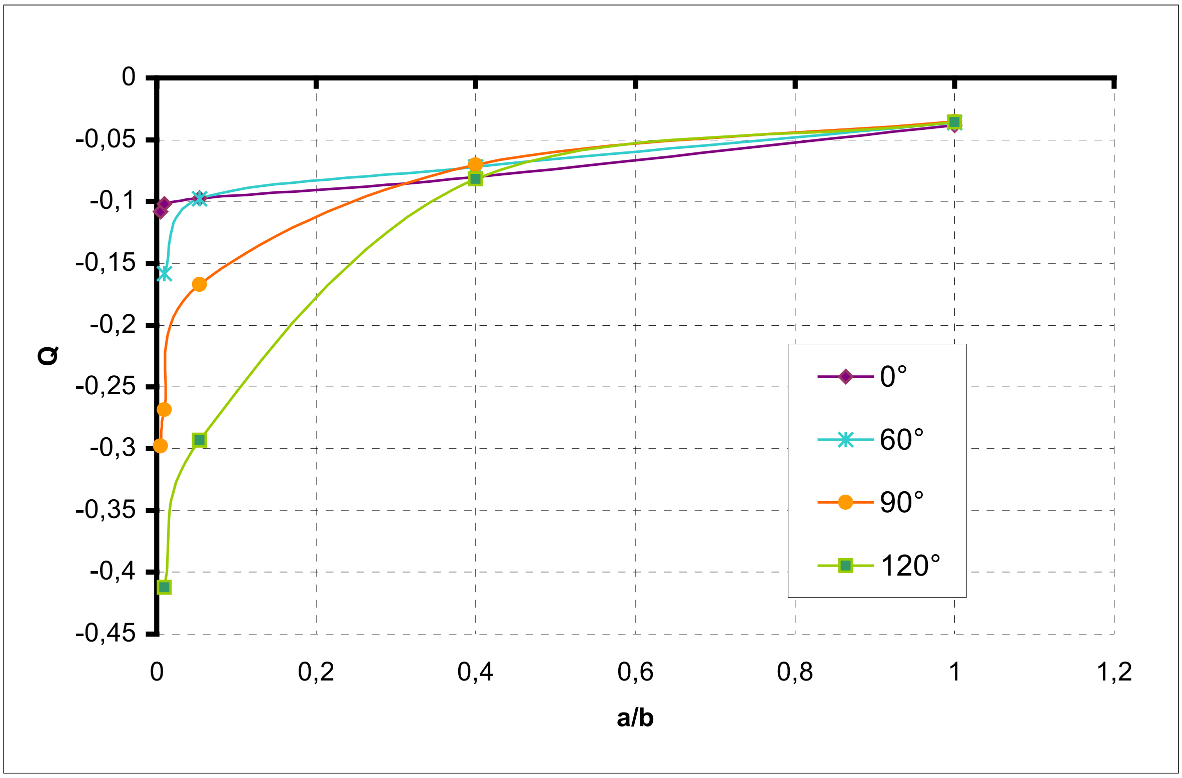

Fig.6. The calculated values of Q-parameter corresponding the case given in Fig.5-A.

Negative value of Q-stress increases the fatigue crack propagation rate.The relationship suggested for long cracks in the paper [4] can be used to quantify the effect. The level of constraint influences the rate of propagation of short fatigue crack more strongly than that of a long fatigue crack. For microstructurally short fatigue cracks, the T-stress strongly depends on the orientation of the crack with respect to the grain boundary. Thus the rate of propagation of a fatigue crack which is properly oriented with respect to the boundary (i.e., where T-stress is negative) may be twice as great due to the constraint effect as that for a long crack. Similarly, the effect of constraint for mechanically short fatigue cracks initiated at the tip of a V-notch can be quantified by using the value of the T-stress. Again, due to constraint, the rate of propagation of a short crack may be much greater than for a long fatigue crack.

Short fatigue cracks generally behave more sensitively to constraint than do long ones. The value of the nominal stress intensity factor K and the T- stress (or Q-parameter) are not adequate to describe the behavior of a short fatigue crack. The local values of both K and T must be used to explain, at least qualitatively, the anomalous behavior of short fatigue cracks.

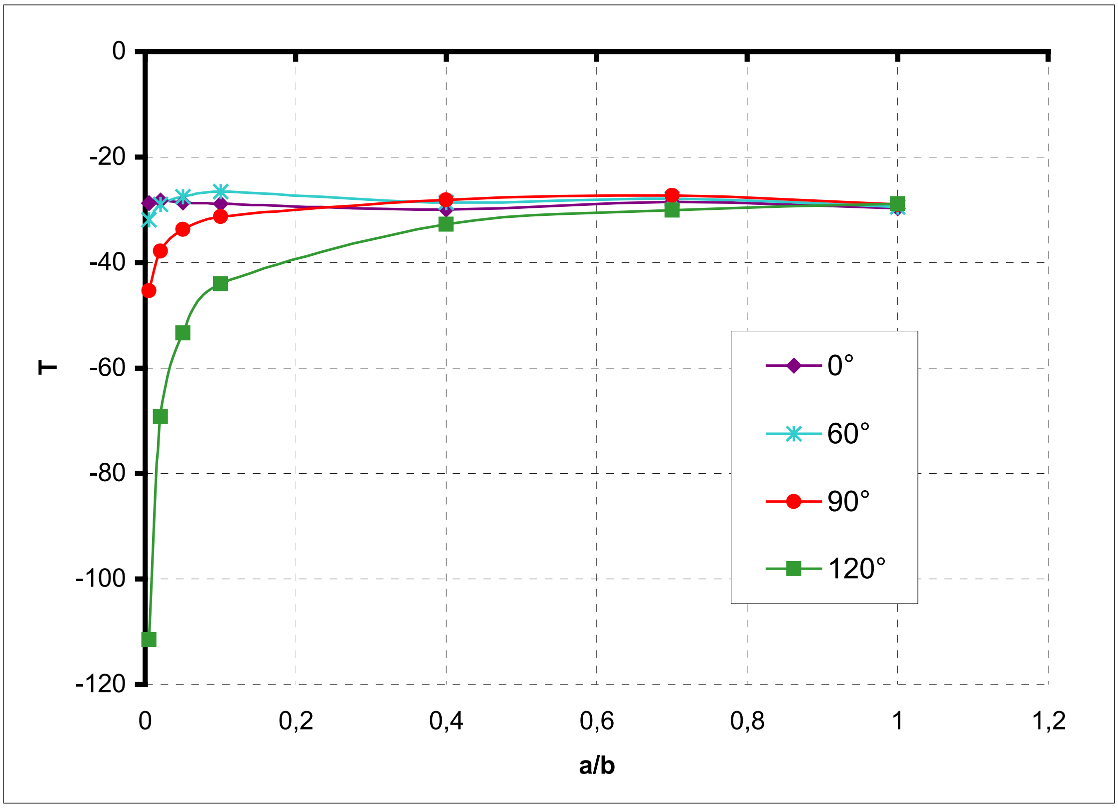

Fig.7. The calculated values of the T-stress corresponding to the case given in Fig.5-B. Negative value of T-stress increases the fatigue crack propagation rate.

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