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ON FATIGUE LIMIT OF NOTCHED COMPONENTS

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ABSTRACT

The most important parameters in defining the fatigue limit and the fatigue notch sensitivity of notched components are identified and analysed. On the basis of the experimental evidence that the fatigue limit (both plain and notched) represents the threshold stress for the propagation of the nucleated short cracks, a material resistance to crack growth as a function of the crack length is suggested, which can be estimated by using mechanical and microstructural parameters obtained through standardized mechanical tests and simple microstructural analysis.

KEYWORDS

Fatigue limit, Notch sensitivity, Microstructural threshold, Mechanical threshold.

INTRODUCTION

The fatigue limit of polycrystalline metals seems to be a function of a maximum non-propagating crack length associated with a particular stress level [1-10]. Up to a certain crack length the crack is non-damaging with respect to the fatigue limit, and for long cracks the fatigue limit decreases with increasing crack length. The effect of crack length on the fatigue limit can be described conveniently by means of Figure 1. It shows the threshold stress (defining the border between propagating and non-propagating cracks), as a function of a crack length. For a microstructurally short crack (MSC, crack length of the order of the microstructural dimensions) initiated from a plain surface, the plain fatigue limit $\Delta\sigma_{e0}$ defines the critical nominal stress range needed for continued crack growth. If the applied stress range $\Delta\sigma$ is smaller than $\Delta\sigma_{e0}$, cracks included in the microstructural short crack regime are arrested at microstructural barriers. On the other hand, the threshold for long cracks

(LC) is defined in terms of the threshold value of the stress intensity range, ΔK_{th}, thus long cracks can only grow by fatigue if the applied ΔK is greater than ΔK_{th}. In the physically short crack regime (PSC, crack length less than that (l) at which crack closure is fully developed), which corresponds to the transition between microstructurally short and long crack regimes (MSC and LC), the threshold is below $\Delta\sigma_{e0}$ and ΔK_{th}. The length d defines the plain fatigue limit and is given by the position of the strongest microstructural barriers.

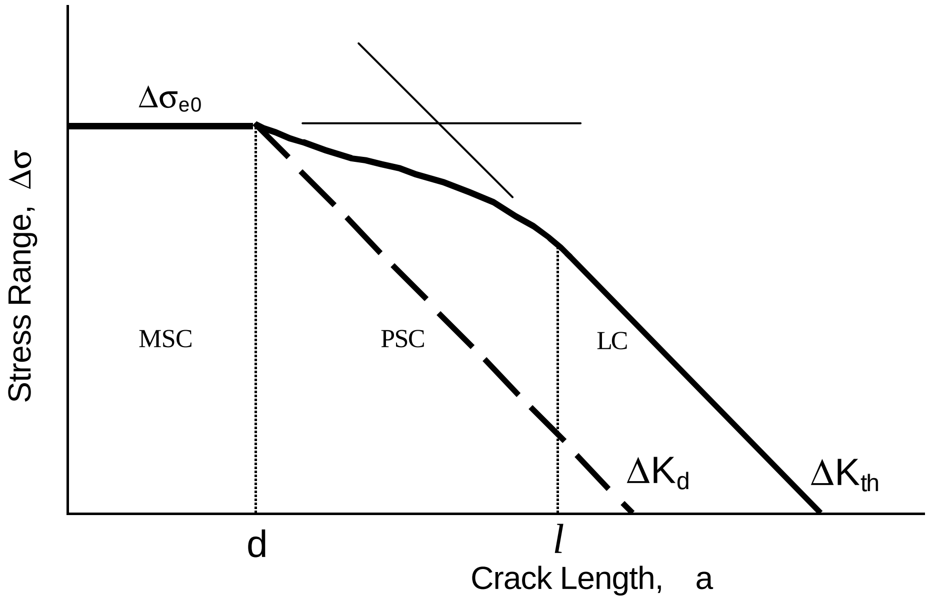

Figure 1. Threshold between propagating and non-propagating cracks.

It has been demonstrated that two patterns of notch fatigue behavior can occur [1-13]. In a smooth specimen once the crack initiate and overcomes the first predominant microstructural barrier at the position d (which defines the plain fatigue limit), the stress level is high enough to drive the crack to fracture [11-13]. As the stress gradient increases due to the presence of a blunt notch, deeper barriers define the fatigue limit, and the difference between the initiation limit and the fatigue limit increases. However, the position d of the first predominant microstructural barrier seems to estimate conservatively the fatigue limit of blunt notches [11-13].

Figure 2 shows the three most important parameters in defining the fatigue limit and the notch sensitivity of notched components [11]. Increasing $\Delta\sigma_{e0}$ (that is to say, increasing the resistance of the predominant microstructural barrier) causes the curve defining the fatigue limit of blunt notches to rise as a whole. If d is increased for a given $\Delta\sigma_{e0}$ and ΔK_{th} (that is to say the distance between two consecutive microstructural barriers is increased), that curve turns upward around the point given by $\Delta\sigma_{e0}$ and $k_t = 1$ (point A), decreasing the fatigue blunt notch sensitivity. For sharp notches the fatigue notch sensitivity is given by the mechanical threshold ΔK_{th} and the notch depth D.

From the above discussion is obvious that in order to develop a model to predict the fatigue limit of notched components, as well as fatigue crack propagation life, it is necessary to obtain an expression for the material resistance to crack propagation as a function of the crack length, including the short crack regime. In this work a material resistance to crack growth as a function of the crack length is suggested, which can be estimated by using mechanical and microstructural parameters obtained through standardized mechanical tests and simple microstructural analysis.

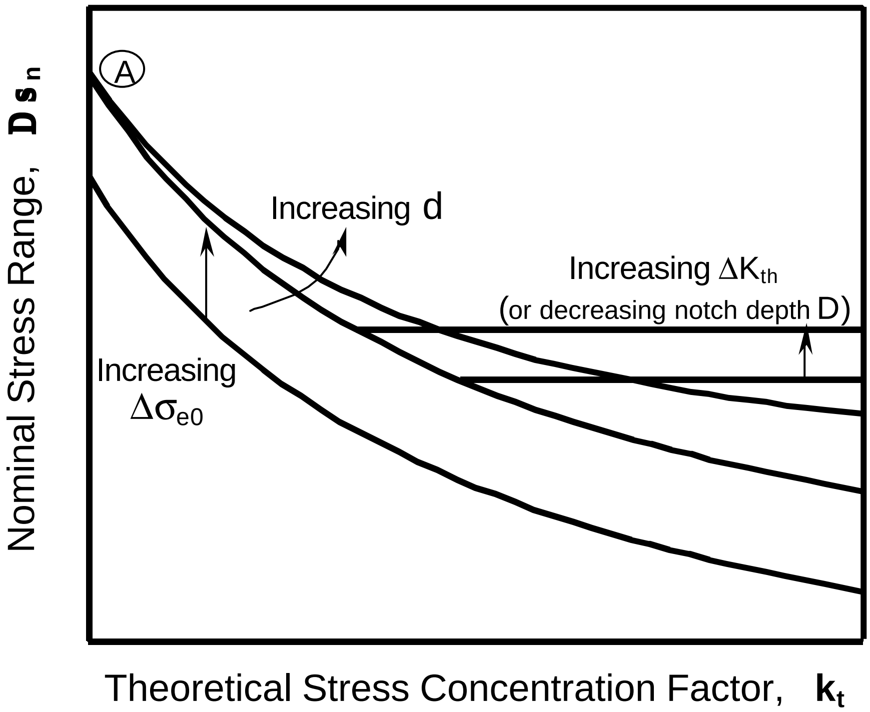

Figure 2. Mechanical, geometrical and microstructural parameters controlling the fatigue limit and fatigue notch sensitivity of notched components.

THRESHOLD STRESS VS. CRACK LENGTH

In the short crack regime, crack closure develops with an increase in crack length [1-10], and this crack closure reduces the effective range of the applied stress intensity factor. So it can be considered as an extrinsic material resistance. In this way a resistance curve to crack propagation can be defined adding the crack closure component of the stress intensity factor to the intrinsic crack grow resistance of the material. An intrinsic material resistance to microstructurally-short crack propagation ΔK_d, can be defined by the plain fatigue limit $\Delta\sigma_{e0}$ and the position of the strongest microstructural barrier *d*, as follows [14]:

$$\Delta K_d = \Delta\sigma_{e0}\sqrt{\pi d} \tag{1}$$

where the plain fatigue limit $\Delta\sigma_{e0}$ represent the effective resistance to crack propagation of the strongest microstructural barrier, and its position *d* defines the notch sensitivity for very blunt notches. It seems reasonable to define the parameter ΔK_d as a microstructural threshold.

The material resistance to crack propagation as a function of the crack length, $\Delta\sigma_{th}(a)$, is then obtained as:

$$\Delta K_{th} = \Delta K_d + \left(\Delta K_{th} - \Delta K_d\right)\left[1 - e^{-k(a-d)}\right] = \Delta\sigma_{th}\sqrt{\pi a} \qquad a \geq d$$

(2)

and then

$$\Delta\sigma_{th} = \frac{\Delta K_d + (\Delta K_{th} - \Delta K_d)\,[1 - e^{-k(a-d)}]}{\sqrt{\pi\, a}} \qquad a \geq d \qquad (3.a)$$

$$\Delta\sigma_{th} = \Delta\sigma_{e0} \qquad a < d \qquad (3.b)$$

Where ΔK_{th} and $\Delta\sigma_{e0}$ (and so ΔK_d), are function of the stress ratio R.

Let find an expression for the factor k to take into account the development of the crack closure component of ΔK_{th}. It has been shown by Lankford [15] that short cracks may grow at the same rate as long cracks when the cyclic plastic zone size r_{pc} is approximately similar to the relevant microstructural dimension. So, we can suppose that the extrinsic resistance to crack propagation ($\Delta K_{th} - \Delta K_d$) has been developed when r_{pc} becomes equal to d.

The cyclic plastic zone size at the crack tip in plane strain condition can be estimated as [16]:

$$r_{pc} = \frac{1}{3\pi}\left(\frac{\Delta K}{2\,\sigma_{ys}}\right)^2 \qquad (4)$$

where ΔK is the applied stress intensity factor range, and σ_{ys} is the yield stress of the material.

At the threshold stress (da/dn = 0):

$$\Delta K = \Delta K_{th} = \Delta\sigma_{th}\sqrt{\pi\, a}$$

We assume that $\Delta\sigma_{th} = \Delta\sigma_{e0}$ and that $\Delta\sigma_{e0} = \sigma_u$ (the strength of the material)[16], so that the cyclic plastic zone size can be estimated with the following expression:

$$r_{pc} \approx \frac{a}{12}\left(\frac{\sigma_u}{\sigma_{ys}}\right)^2 \qquad (5)$$

In Eqn 2 the extrinsic crack growth resistance (second term in right hand) is equal to 87% of the total one when $k\,a = 2$ (with a >> d). We here suppose that at this state the extrinsic crack growth resistance is totally developed. Supposing that this also occur when $r_{pc} = d$, we get the following condition:

$$r_{pc} \approx d \approx \frac{a_{r_p=d}}{12}\left(\frac{\sigma_u}{\sigma_{ys}}\right)^2 \qquad (6)$$

From Eqn 6, and with the condition $k\, a_{rp=d} = 2$, we get the following expression to estimate the parameter k:

$$k \approx \frac{1}{6\,d}\left(\frac{\sigma_u}{\sigma_{ys}}\right)^2 \qquad (7)$$

Expressions (3) and (7) define a material resistance curve that can be estimated with the plain fatigue limit $\Delta\sigma_{eo}$, the position of the strongest microstructural barrier d, the mechanical threshold for long crack ΔK_{th}, the yield stress σ_{ys} and the strength σ_u of the material. These are mechanical and microstructural parameters, which can be obtained through standardized mechanical tests and simple microstructural analysis.

Figure 3 shows the crack growth resistance curve for a pressure vessel steel of the type 2.25 Cr 1 Mo (Yield Stress σ_{ys} = 400 MPa, Tensile Strength σ_u = 580 MPa, plain fatigue limit $\Delta\sigma_{e0}$ = 500 MPa, and threshold for long crack ΔK_{th} = 12 MPa $m^{1/2}$) [4]. Some experimental results obtained from the literature are also shown [4]. The distance between predominant microstructural barriers to crack propagation d can be supposed (see for instance ref. [11]) given by the mean packet size of bainite, 0.025 mm [4]. It can be seen that expression (3) predicts reasonably well the experimental results.

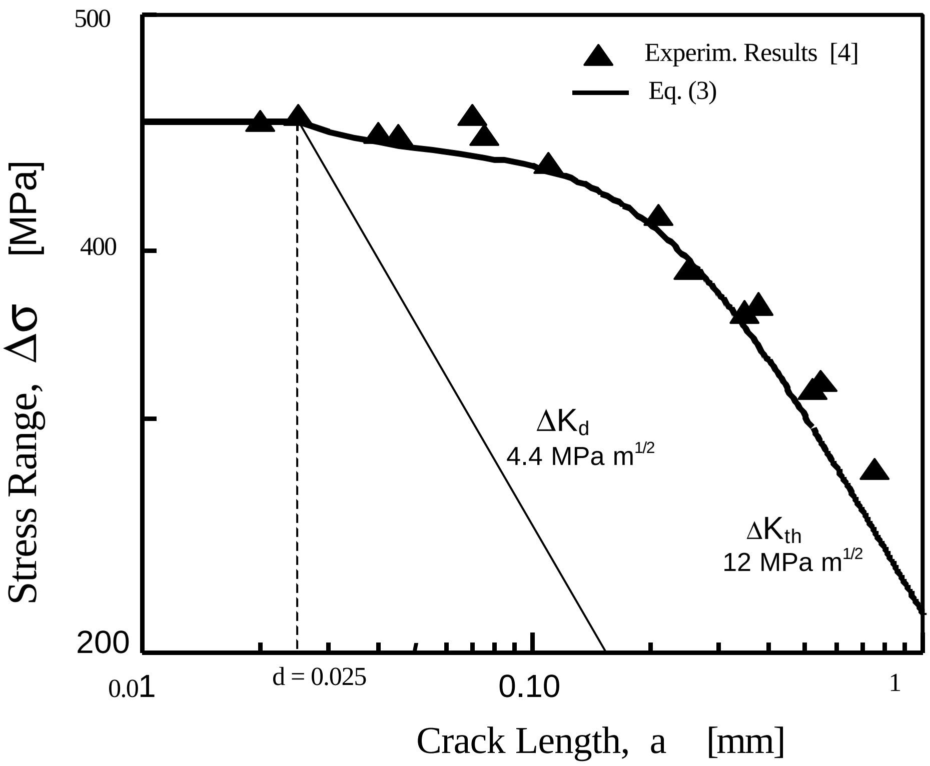

Figure 3. Estimated crack growth resistance for a pressure vessel steel of the type 2.25 Cr 1 Mo. Experimental results [4] are also included.

CONCLUSIONS

An expression for the material resistance to crack propagation as a function of the crack length is obtained from a depth given by the position *d* of the strongest microstructural barrier to crack propagation, which defines the plain fatigue limit. The plain fatigue limit $\Delta\sigma_{e0}$ and the position *d* define an intrinsic material resistance ΔK_d (microstructural threshold to crack propagation). An extrinsic threshold to crack propagation is defined by the difference between the mechanical threshold to crack propagation for long crack ΔK_{th} and the microstructural threshold ΔK_d, as a function of the crack length *a*.

A crack growth resistance curve is estimated for a pressure vessel steel, which seems to predict reasonably well experimental data.

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