THE CHARACTERISTICS OF THRESHOLD ΔK_{th} VALUE FOR FATIGUE CRACK PROPAGATION OF SHALLOW CRACK

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I. INTRODUCTION

The threshold ΔK value for fatigue crack propagation (ΔK_{th}) is an important parameter for engineering design and usually determined with typical specimens of deep crack. However,there rarely exists such a deep crack in engineering components, a question is naturally raised, what is the effect of the crack depth on the ΔK_{th} value? In order to answer this question and to meet the demands of different industrial applications, we have investigated the effects of the crack length, load ratio and overloading on ΔK_{th} value and searched the fundamental causes of these effects since 1978. Recently, more investigators are interested in this problem[1], and some systematic works were reported on surface crack[2] and single notched crack[3]. A detailed summary of our work is presented as follows.

II. EXPERIMENTAL PROCEDURES AND RESULTS

The steels used in this investigation are 2Cr13 (YS=86 kg/mm^2), 34CrNi3Mo (YS=65-70kg/mm^2), 40Cr (YS=50kg/mm^2) and A3 (YS=25kg/mm^2). Room temperature fatigue tests were performed in the Amsler fatigue testing machine with f=80Hz and different load ratio (R=0.1 and 0.6). The standard three-points bending specimens were used. For deep crack specimens, the crack length was measured with a microscope of ten-times magnification. For shallow crack specimens, the crack length was measured by heat-tinting method, and the average crack length on the fracture surface after heat-tinting (Figure 1) was used. The stress intensity factor was calculated

$$K_I = \frac{PS}{BW^{3/2}} F(\frac{a}{W}) \qquad (1)$$

$$F(\frac{a}{W})=2.9(\frac{a}{W})^{1/2}-4.6(\frac{a}{W})^{3/2}+21.8(\frac{a}{W})^{5/2}-37.6(\frac{a}{W})^{7/2}+38.7(\frac{a}{W})^{9/2} \qquad (2)$$

which is valid for $0<(a/W)\leqq 0.6$.

The fatigue pre-cracked specimens were ground and polished to the required crack depth, and all specimens were annealed together to relieve the residual stress and to ensure the same microstructural state for all comparison.

The experimental results are summarized as follows.

(1) The Effect of Crack Length on ΔK_{th}

As shown in Figure 2: when $a/W\leqq 0.1$ (or $a\leqq 2.0$mm), ΔK_{th} increases exponentially with the increase of a/W; when a/W>0.1, ΔK_{th} is constant regardless of the change of a/W. It should be emphasized that ΔK_{th} is a constant material property only for rather deep (a/W>0.1) crack.

(2) The Effect of Load Ratio and Yield Strength on the Drop of ΔK_{th}

We selected a/W=0.03 (i.e., a ≈ 0.7mm) as shallow crack, and denoted the difference between shallow crack ΔK_{th} and that for deep crack as the drop of ΔK_{th}. Both Figure 3 and Table 1 indicate that the drop of ΔK_{th} is decreased with the increase of R value from 0.1 to 0.6 and with the increase of yield strength of the materials. It is interesting to point out that not only the drop of ΔK_{th} but also the deep crack ΔK_{th} itself is decreased with the increase of the yield of the materials (Table 1).

(3) Overload Effect on ΔK_{th} of Specimens with Different Crack Length

We select the ratio m to express the degree of overloading, i.e., when m=1, there is no overloading; when m=2, there is 100% overloading, etc. Figure 4 shows that overloading increases ΔK_{th}, and the increase is more for deep crack than that for shallow crack.

In order to find out the possible reasons for the drop of ΔK_{th} due to the decrease of the crack length, we selected aluminum alloy specimens to investigate the effect of the crack length on the plastic zone in front of the sharp notch with optical microscopy and holographic interference technique. Both the optical observations (figures 5 and 6) indicate that for the same value of K,the shallow notch exhibits larger plastic zone and more severe plastic deformation within the plastic zone.

Table 1 K_{th} for Deep Crack and the Drop of ΔK_{th}

Steel	yield strength (kg/mm^2)	ΔK_{th}(deep crack) R=0.1,$kg/mm^{3/2}$	Drop of ΔK_{th}*%	
			R=0.1	R=0.6
2Cr13	86	22	27.6	----
34CrNi3Mo	68	26	35.8	18.0
40Cr	50	27	33.2	----
A3	24	35	45.7	28.8

* $[(\Delta K_{th})_{deep} - (\Delta K_{th})_{shallow}]/(\Delta K_{th})_{deep}$

III. DISCUSSIONS

For plain specimens, it is well known from the microscopic observation that the nucleation of the fatigue crack is due to the formation and extrusion of the persistant slip band[4]. Furthermore, in order for the fatigue crack to nucleate at all, the applied cyclic strain must be above a certain level; otherwise, the fatigue life of the plain specimen tends to be infinite. Based upon these facts, if the propagation of the fatigue crack is considered as the re-nucleation of the crack in front of the pre-existing crack, it may be deduced that the premise of the non-propagation of fatigue crack is: the amplitude of the average plastic cyclic strain within a certain "structural region" (δ_0) in front of the crack tip should be below a certain value, i.e.:

$$\overline{\Delta\varepsilon_p} \leqq \text{constant} \tag{3}$$

Referring to Figure 7, $\overline{\Delta\varepsilon_p}$ can be calculated as an average value within δ_0 and subtending an angle $\Delta\theta$:

$$\overline{\Delta\varepsilon_p} = \frac{1}{\delta_0^2\Delta\theta/2}\int_0^{\delta_0}\Delta\varepsilon_p r\Delta\theta dr \tag{4}$$

From the results given by References [5] and [6] for $\Delta\varepsilon_p$, we obtain:

$$\overline{\Delta\varepsilon_p} = 2\varepsilon_s\left(\frac{2\Delta\omega_0}{\delta_0} - 1\right) \tag{5}$$

where ω_0 is the size of the plastic zone under cyclic loading, and ε_s is the yield strain under cyclic loading. Combining equation (3) and (5) and considering ε_s to be a constant, we obtain:

$$\Delta\omega_0/\delta_0 \leqq \text{constant} \tag{6}$$

As an approximation, we use the $\Delta\omega_0$ expression for mode III loading[7]:

$$\frac{\Delta\omega_0}{a} = \left(\frac{\Delta\sigma}{2\sigma_s}\right)\left(1 + \frac{4}{\pi}\frac{\left(\frac{\Delta\sigma}{2\sigma_s}\right)^2}{1-\left(\frac{\Delta\sigma}{2\sigma_s}\right)^2}\right) \tag{7}$$

where σ_s is the yield strength of the material. For deep crack, $(\Delta\sigma/2\sigma_s)<<1$, the above equation is simplified as:

$$\Delta\omega_0 = (\Delta K_I)^2/4\pi\sigma_s^2 \tag{8}$$

Substituting into equation (6) for threshold condition:

$$\Delta K_{th}/\delta_0 = \text{constant} \tag{9}$$

i.e., ΔK_{th} is a constant for deep crack as found experimentally (Figure 2). However, for shallow crack, $\Delta\sigma/2\sigma_s$ is no longer small, and from equations (7) and (8), we obtain:

$$\Delta\omega_0 > (\Delta K_I)^2/4\pi\sigma_s^2 \tag{10}$$

which agrees with what we have found experimentally (Figures 5 to 8).

The fact that very shallow crack exhibits lower ΔK_{th} (Figures 2 to 4 and Table 1) can be explained as follows:

(1) Very shallow crack exhibits more severe plastic deformation (Figures 5 and 6) for the same K_I, therefore lower ΔK_I is required to satisfy the non-propagation criterion (Equation 2), i.e. lower ΔK_{th}.

(2) The very shallow crack tip is very close to the surface, therefore the residual compressive stress during the unloading of fatigue cycle is much easier to be released. The crack body with very shallow crack has higher rigidity. Both effects lead to lesser closure effect for very shallow crack and lesser effect of overloading (Figure 4). In other words,

$\Delta K_I \gtrsim \Delta K_{Ieff}$ for very shallow crack and $\Delta K_I > \Delta K_{Ieff}$ for deep crack.

(3) There might be some difference in the size of "structural region" (δ_0) which needs to be further investigated.

In general, material with lower yield strength (σ_s) will show smaller yield strain (ε_s), therefore from equation (5), larger ΔK_{th} (which affects $\Delta\omega_0$) would be required to satisfy the threshold criterion (equation 3). This is what we found experimentally (Table 1). The effect of the yield strength upon the drop of ΔK_{th} needs further explanation.

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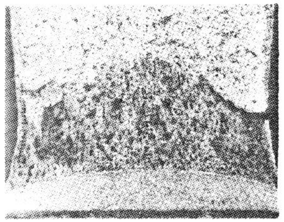

Fig. 1

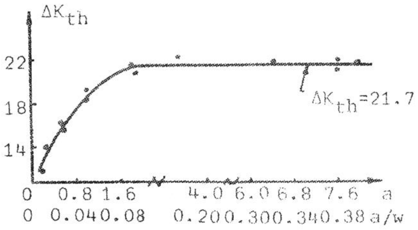

Fig. 2

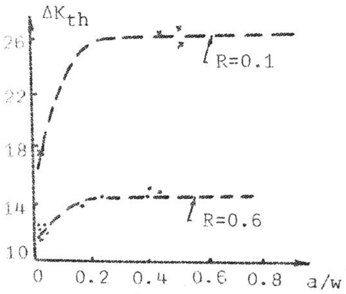

Fig. 3

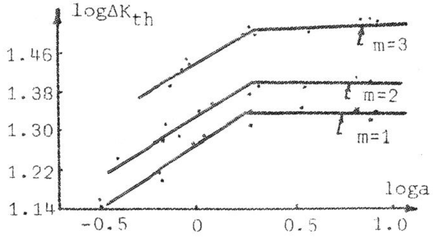

Fig. 4

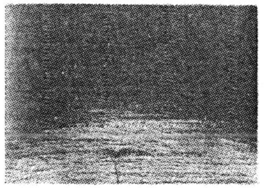

Fig. 5

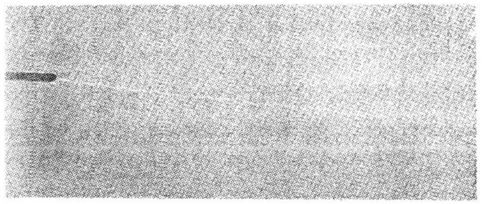

Fig. 6

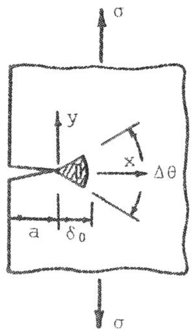

Fig. 7