# FATIGUE THRESHOLDS OF A LOW-ALLOY STEEL WITH SHALLOW SEMI-ELLIPTICAL SURFACE CRACK

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## INTRODUCTION

The interest in the fatigue threshold($\Delta K_{th}$) as a design criterion and a parameter of material property has been greatly increased in recent research work, but many problems yet remain to be resolved. The values of $\Delta K_{th}$ found in literature, are usually obtained by using deep-cracked specimens and load shedding procedures. However such long crack and load reduction process are seldom found in the most of machine parts and metallic constructions.

Topper et al.[1] found that the values of $\Delta K_{th}$ are varying with crack length. Ritchie[2] expounded this trend and gave an explanation of the strength effect in steel . It states that unlike endurance limit the fatigue threshold is decreasing with increasing strength. In addition, in conventional procedure of $\Delta K_{th}$ test the material in the region immediately ahead of crack tip is inevitably damaged during the test by overstressing.

Surface cracks are common flaws in many machine parts and structures. The growth of surface-initiated fatigue cracks may be a major factor in determining the overall endurance life of a machine part. Unfortunately the $\Delta K_{th}$ data for surface crack especially short surface crack are limited in prevailing literature.

In the present paper, we attempt to investigate the fatigue thresholds of certain steel with different level of strength, through testing two types of specimens, i.e. through-thickness long cracks and shallow surface cracks.

## EXPERIMENTAL PROCEDURE

A medium carbon 3% chromium-molybdenum-vanadium steel (En 40c), austenitised at 920°C, quenched in oil and then tempered at temperatures of 200°, 350°, 500°, 650° and 700°C respectively, has been used in the present work. The chemical composition and the fundamental mechanical properties of the steel are given in Table I, II. The single-edge-notch specimens of size 20×20×100mm were used. We measured the fatigue thresholds of the steel with the conventional load shedding procedures[3].

Table I Composition of En 40c Steel

| C | Si | Mn | P | S | Cr | Mo | Ni | V |
|---|---|---|---|---|---|---|---|---|
| 0.40 | 0.34 | 0.62 | 0.005 | 0.010 | 3.12 | 1.07 | 0.25 | 0.24 |

Table II Fundamental Mechanical Properties

| Tempering temper. °C | Mono. $\sigma_{ys}$ MN m$^{-2}$ | Cycl. $\sigma_{ys}$ MN m$^{-2}$ | $\sigma_u$ MN$^{-2}$ | Elong. % | Area Reduc. % |
|---|---|---|---|---|---|
| 200 | 1604 | 1079 | 2117 | 13.1 | 40.2 |
| 350 | 1612 | 1000 | 1900 | 13.6 | 44.6 |
| 500 | 1478 | 937 | 1700 | 14.3 | 47.8 |
| 650 | 947 | 902 | 1058 | 18.6 | 64.3 |
| 700 | 855 | 681 | 969 | 24.1 | 66.1 |

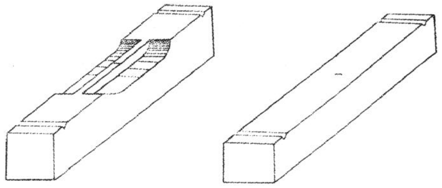

Fig. 1 Preparation of thumbnail crack in specimen

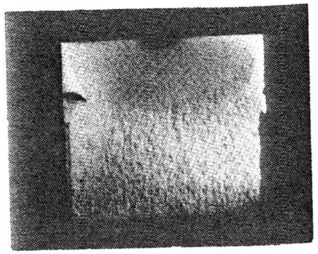

Fig. 2 Optical micrograph of fracture surface

Following Knott[4], the process of producing a short semi-elliptical (thumbnail) crack is shown in Fig. 1. A 2mm wide ridge was left on the top surface of specimen then a slot was made on it with a thin slit wheel. The specimen was fatigue precracked, and the fatigue crack initiated from the slot on the ridge and propagated into the bulk of the specimen. Then the specimen was heated at the temperature lower than the temper temperature so as to relieve possible residual stresses introduced by fatigue precracking and gave an oxidation colour to the pre-cracked surface. Finally, the ridge was removed through grinding to leave a short semi-elliptical surface crack of required length in the remaining rectangular section.

All of the fatigue specimens were tested on MAND electronic servohydraulic fatigue test machine. The load ratio was kept constant, R=0.333. The crack was monitored continuously by electrical potential technique with the sensitivity of 0.5 μv and was measured with a microscope under 100x magnification periodically. The $\Delta K_{th}$ for surface crack on the other hand, were measured by load step increment test program (i.e. "ascend stairs"). The $\Delta K_{th}$ values were referred to the stress-intensity at a crack growth rate less than $10^{-7}$ mm/cycle. After specimens were broken by fatigue, the shape and size of fatigue pre-cracks were checked on the fracture surface with microscope (Fig. 2). The K values were calculated using the relationship from Rooke and Cartwright[5], i.e.

$$K = 6QM\ (\pi C)^{\frac{1}{2}}/BW^2 \qquad (1)$$

where Q=crack shape factor, M=cyclic bending moment, C=maximun crack depth, B=specimen width and W=specimen thickness. This solution was obtained by Shah and Kobayashi[6] with an approximate error up to 5%.

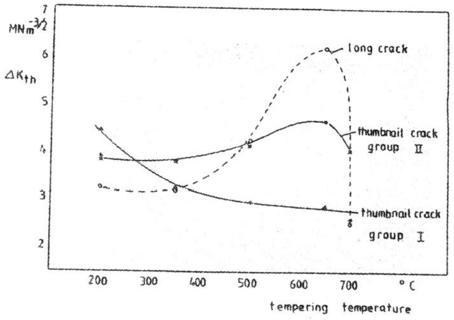

Fig. 3 $\Delta K_{th}$ Vs. tempering temperature(°C)

## RESULTS

The $\Delta K_{th}$ are shown as a function of tempering temperature in Fig. 3.

The variation trend of $\Delta K_{th}$ associated with through-thickness deep-cracked specimens tempered at 200°, 350°, 500°, 650°C agrees with that of 300M steel from the Ritchie's paper[2]. A ramarkable feature, is that a very low $\Delta K_{th}$ value was obtained for specimen tempered at 700°C, giving a peak in the curve of $\Delta K_{th}$ vs. tempering temperature. Such peaks had been observed earlier for a 40Cr (similar to 4140) steel and a high carbon tool steel[3].

The results of test on Group I specimen with semi-elliptical crack show that as the depth of crack is within the range of 0.08–0.61mm $\Delta K_{th}$ values of steel tempered at various temperatures from 200°C to 700°C have the same trend as that of the fatigue strength i.e. the higher the strength, the higher the fatigue threshold $\Delta K_{th}$.

The curve of Group II specimen for semi-elliptical cracks with the depth ranging from 1.24 mm to 2.95mm seems more or less flattened. There appears a peak value of $\Delta K_{th}$ at 650°C tempering temperature.

## DISCUSSION

The expression for the fatigue-crack propagation threshold proposed by Weiss and Lai[7] is in the form

$$\Delta K_{th} = \sigma_c \sqrt{\frac{3\pi}{2}\rho^*} \qquad (R=0) \qquad (2)$$

where $\sigma_c$ is the local material strength ahead of the crack front and $\rho^*$ is limiting microstructural dimension. Hence, it is conjectured that the optimum combination of strength and micro-structural size will result in an optimal value of $\Delta K_{th}$ . However, the applicability of the eq. 2 is limited to cracks with sufficient length. For short crack, Topper[1] suggested the following relation:

$$\Delta K_{th} = \Delta\sigma_{th}\ \sqrt{\pi(1 + l_0)} \qquad (3)$$

where $\Delta\sigma_{th}$ is the threshold stress, $l_0$ is a constant for a given material which varies linearly with the grain size. Xiao[8] and his co-workers found that in the case of short crack (say, a/w = 0.05), the $\Delta K_{th}$ values are decreasing, but the plastic zone at the tip of short crack is much more pronounced than that of long crack. The fact implies that the elastic-plastic analysis for short crack is essential, and LEFM is no longer adequate. A simple way is to estimate the plastic zone size at the short crack tip and an effective crack length is assumed which takes the actual crack length plus some fraction of the plastic zone size. As first approximation, this increment may take the plastic zone radius so that

$$K_{eff} = y\,(\frac{a+r_y}{W})\,\sigma\sqrt{a + r_y} \qquad (4)$$

Since the plastic zone itself depends on the stress intensity factor, the value of $K_{eff}$ should be calculated by iteration. For sake of simplification, an infinite plate with a small central crack is considered. Then, $K_{eff}$ can be determined directly, i.e.

$$K_{eff} = \sigma\sqrt{\pi a[1+\tfrac{1}{2}(\frac{\sigma}{\sigma_{ys}})^2]} = K\sqrt{1+\tfrac{1}{2}(\frac{\sigma}{\sigma_{ys}})^2} \qquad (5)$$

It is seen that $K_{eff}$ is always greater than K. Thus, for a given K, $K_{eff}$ is expected to have higher value for low strength materials and in the case of short crack (i.e. high stress).

By comparing eq. (3) and eq. (5), it is reasonable to relate Topper's $l_0$ with the size of plastic zone ahead of short crack tip, so we may write

$$\Delta K_{th} = \Delta\sigma_{th}\sqrt{\pi[a+r_y]} = \lim_{a\to r_y} \sigma_e\sqrt{\pi\beta(\frac{\sigma_e}{\sigma_{ys}})^2} \qquad (6)$$

The empirical relationship of fatigue limit $\sigma_e$ and ultimate strength $\sigma_u$ (i.e. $\sigma_e = (0.35\text{–}0.50)\sigma_u$) is well known. It indicates that in the case of short crack ($a \to r_y$), the fatigue threshold $\Delta K_{th}$ increases with increasing strength. This is onsistent with the results obtained during 1930's to 1950's before the fracture mechanics approach is applied to the field of fatigue. Rotating bending fatigue limit for cylindrical specimens containing an artificial circumferential crack have the same trend as the plain fatigue limits, i.e. both plain fatigue limits and fatigue limits of cracked specimens increase with increasing strength[10].

For the steel quenched and tempered at low temperatures, both fatigue threshold and fatigue limit decrease with increasing the crack length. Tentatively, high fatigue notch sensitivity may be responsible for the degradation of the fatigue resistance.

## CONCLUSIONS

1. Fatigue thresholds for very short semi-elliptical cracks increase with increasing strengh of the steel, i.e., the higher the strength, the higher $\Delta K_{th}$ will be.

2. Fatigue thresholds for medium length semi-elliptical cracks give the same varying trend as that for long through crack.

3. The electrical potential technique and load step increment procedure are adoptable to determine the fatigue threshold of short surface cracks.

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