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FRACTURE TOUGHNESS OF THERMALLY FATIGUED MATERIAL

N. G. Ohlson*

INTRODUCTION

In modern engineering design, rapid heating and cooling is quite often encountered and the transient stresses produced in each cycle may cause fatigue of the material if they are sufficiently high and if the number of thermal cycles is sufficiently large.

For the interpretation of strain cycling results and for predicting the number of cycles to failure of a certain component, various relationships like the Coffin-Manson law Reference [1] have proved to give a very close fit. Such an equation is not valid, however, if a sharp defect, e.g., a crack, is contained in the material. Fracture mechanics provides the tool for the mathematical treatment of this problem.

The present paper is aimed at giving some information concerning the change of mechanical properties of the material near a sharp defect when the material is subjected to thermal fatigue.

FORMULATION OF THE PROBLEM

For plane strain, the fracture toughness is a characteristic constant of the material, determining when crack growth sets in. In mode I loading, this constant is denoted by K_{Ic}. It is sensitive to the way of manufacturing the material, e.g., the heat treatment.

In thermal fatigue, several physical effects are acting simultaneously, thus making the complete procedure very difficult to analyze.

The question posed in this paper is whether there is a noticeable change in fracture toughness as a result of the thermal cycling. If this is the case, the next problem would be to estimate the change in K_{Ic} in such a way that it can be used in the design of components subjected to thermal fatigue.

EXPERIMENTAL PROCEDURE

Three-point-bend specimens were manufactured according to Figure 1. In each of these, a fatigue crack was grown from the bottom of the notch. After that the specimens were subjected to a number of thermal cycles, varying between two and ten. Each cycle consisted of a slow and almost uniform heating in an oven, followed by a rapid quenching in water of one surface of the specimen, Figure 2. As the transient temperature distribution is known through measurement and computation, the stress-intensity

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*The Royal Institute of Technology, Department of Strength of Materials and Solid Mechanics

factor caused by quenching can be estimated. This may be done in the following way.

The stress field is assumed to be uniaxial and varies only with time, t, and with distance perpendicular to the cooled surface, z, i.e.

$$\sigma_x = \sigma_x(z,t)$$

σ_x is the first calculated without considering the notch and the crack, using the conditions of equilibrium

$$M = \int_A \sigma_x \cdot z \cdot dA = 0 \quad \text{and}$$

$$N = \int_A \sigma_x \cdot dA = 0 ,$$

M being the bending moment and N the normal force on the section, which both vanish. By superimposing a stress distribution of the same magnitude as σ_x but of opposite sign for those values of z which correspond to the extent of the notch and crack, this region is unloaded, which is equivalent of introducing the notch and crack, Figure 3.

Since σ_x is a linear function of z, the stress-intensity factor caused by the quenching can be obtained from reference [2]. Results are summarized in Table 1.

TESTING MATERIAL

The material chosen for this investigation was a Swedish tool steel intended for use in hot-working (extrusion of brass, stamping, etc.), Stora 368, with the following approximate composition, C 0.40, Si 0.3, Mn 0.3, Cr 3.3, Mo 1.3, W 2.5, Co 1.7 and V 1.3%.

After quenching from 1050°C in oil, it was annealed for two hours at 650°C. The hardness was approximately 45 HRC and the yield stress at room temperature 750 MN/m^2. The total number of thermally fatigued specimens was 20.

THERMAL FATIGUE TREATMENT

The specimens were heated to three different temperatures, 530°, 600° and 650°C and cooled from these temperatures in the manner described above. None of these treatments was powerful enough to achieve a stress-intensity factor sufficiently high for crack propagation to occur during the cooling. This was done purposely, since the main purpose of the investigation was to observe the behaviour of the material at the crack tip during thermal cycling.

In each treatment, reference specimens were included. These were heated in the same manner as the others but they were not subjected to thermal stresses. By comparing the fracture toughness of reference specimens with that of specimens exposed to thermal stresses it should be possible to study the effect of thermal stresses separately.

ESTIMATE OF THE EXTENT OF THE ZONE AFFECTED BY THERMAL CYCLING

After the thermal cycling, certain specimens were again subjected to conventional fatigue in bending, similar to the previous treatment for producing a crack. Others were not fatigued afterwards. Various crack lengths were obtained in this second stage of mechanical fatigue. If the thermal fatigue affects the fracture toughness only in a limited zone around the original crack tip it might be possible to determine the size of this zone by changing the crack length. It is assumed that the fracture toughness of the material just at the "new" crack tip is determined in a conventional fracture toughness test.

DETERMINATION OF FRACTURE TOUGHNESS

The fracture toughness was determined in the usual way in an Amsler testing machine. Force F and crack opening displacement COD were registered. Figure 4 shows a characteristic curve for the present material. Crack extension is said to occur when the force reaches the value causing the first pop-in or otherwise at the value of maximum force. All the K_{Ic} measurement were made at room temperature.

CORRECTION FOR THE HEAT TREATMENT IN THE THERMAL CYCLE

As mentioned earlier, the fracture toughness is increased in the course of any kind of heat treatment. High temperature and long holding times make the effect stronger. Experimental results for the present material, obtained from the reference specimens, are shown in Figure 5. This increase in K_{Ic} which stems from the heat treatment is subtracted from the measured values of K_{Ic} of thermally cycled specimens, using Figure 5.

RESULTS

Fracture toughness

The change in fracture toughness δK_{Ic}, corrected according to the previous paragraph, as a function of the number of thermal cycles, n, is shown in Figure 6 for the three different maximum temperatures of the cycle.

The plot includes the results of all specimens, regardless whether they were fatigued afterwards in bending or not and regardless of the length of the new secondary fatigue crack. The largest difference in crack length between specimens was of the order of 0.6 mm.

No significant difference between results from specimens with various secondary crack length was observed. This indicates that the effect of the thermal cycling on the material is not limited to a small zone near the first crack tip.

Crack initiation and propagation

An attempt was made to estimate the effect of the thermal cycling on the material properties governing the initiation and propagation of a new fatigue crack after the thermal cycling. The results are summarized in Table 2, which gives the secondary crack length attained after 1000 cycles of loading. The number of cycles counted for obtaining a certain crack length also includes the time needed for re-initiation of a crack.

FRACTURE SURFACE OBSERVATIONS

The fracture surfaces were examined in a Jeol scanning electron microscope. Special attention was devoted to the region where the crack tip was found during the thermal cycling.

Figure 7a shows an over-all view of the fracture surface. The area of primary fatigue is dark because of oxidation. Pellets of metal oxides are seen in Figure 7b.

On comparing the crack tip of the primary fatigue of a specimen subjected to thermal cycling, Figure 7c, and the crack tip of a specimen which was only subjected to an equivalent heat treatment, Figure 7d, it is seen that the tip of the latter (7d) is rather sharp whereas it is blunted in the former specimen (7c).

EXPERIMENTAL ESTIMATE OF THE STRESS INTENSITY FACTOR

In order to investigate whether the assumption of blunting of the crack tip during thermal cycling is correct, the in-plane displacements on the specimen surface were determined by means of speckle interferometry, Figure 8, reference [4]. The results indicate that K_I is reduced. However, some caution should be observed in drawing conclusions from this fact, as it was based on surface measurements only.

DISCUSSION

The fact that the "soft" kind of thermal cycle produces an increased fracture toughness whereas a "hard" cycle gives a decreased toughness indicates that several competitive effects may be present. A possible mechanism which accounts for the results may consist of the following effects.

1. Formation of brittle oxides on the crack surfaces may reduce the toughness.

2. Local yielding occurs readily near the crack tip at the elevated temperature of the thermal cycle. This "pre-straining" of the material may reduce the fracture toughness K_{Ic}, reference [3].

3. Blunting of the crack tip may also occur during the cycling. This is equivalent to a reduction of the stress-intensity factor for a given load, K_I, which might appear in the experimental results as an increased value of K_{Ic}.

An analysis of the stress σ_x as a function of time shows that the region around the crack is subjected to compression for some time after the stress-intensity factor reached its maximum.

Generally speaking, thermal stresses seem to reduce K_{Ic}, except, possibly, when the cycle is "soft".

The results of Table 2 show that crack growth occurs more readily in material subjected to a "soft" thermal cycle. The range of the stress-intensity factor was the same for all specimens in the mechanical fatigue. For experimental reasons, it was impossible to distinguish between initiation and propagation of the secondary fatigue crack. A crack monitor working according to the principle of eddy-current detection was placed on the surface of the specimen across the crack tip. It senses crack growth of the order of 0.1 mm. In the present set-up, the detector revealed a long initiation period, whereas the growth then proceeded with much the same velocity in all specimens. Consequently, the difference between the values of Table 2 should be referred mostly to initiation.

This behaviour may be explained if blunting is assumed to exist. The blunting effect makes the initiation of the new fatigue crack more difficult. A hard cycle will cause blunting more rapidly than a soft.

Thus, several effects may control the fracturing behaviour of thermally fatigued material. The present study only deals with thermal fatigue at low values of ΔK_I. Heat treatment may increase K_{Ic}. The formation of brittle oxides as well as pre-straining, on the other hand, may reduce K_{Ic}. Blunting of the crack tip will reduce K_I, which, in a test for measuring K_{Ic}, will appear as an increased fracture toughness.

REFERENCES

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Table 1

T_{max} (°C)	$K_{I\ max}$ MPa·m$^{1/2}$
530	16
600	20
650	22

Table 2

T_{max} (°C)	Crack length per 1000 cycles (mm)
530	0.033
600	0.024
650	0.014

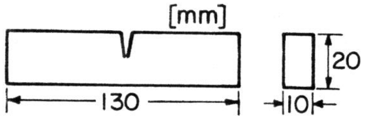

Figure 1

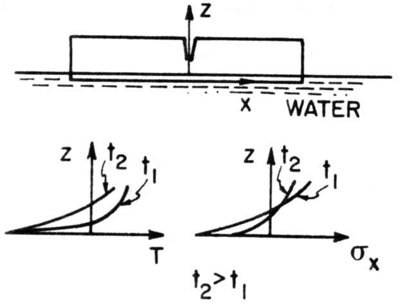

Figure 2

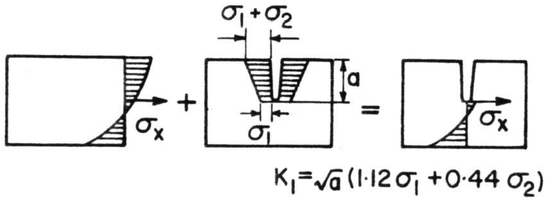

Figure 3

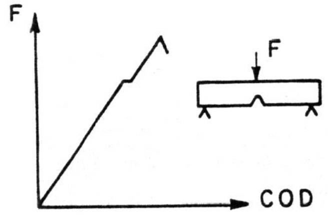

Figure 4

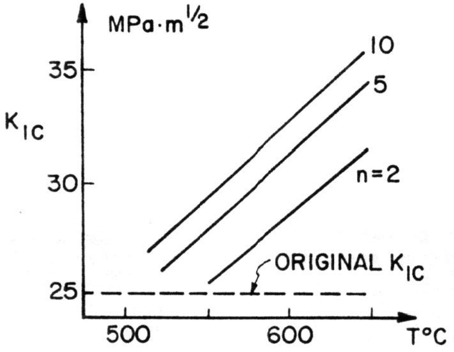

Figure 5

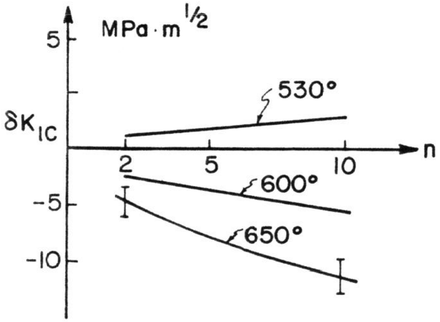

Figure 6

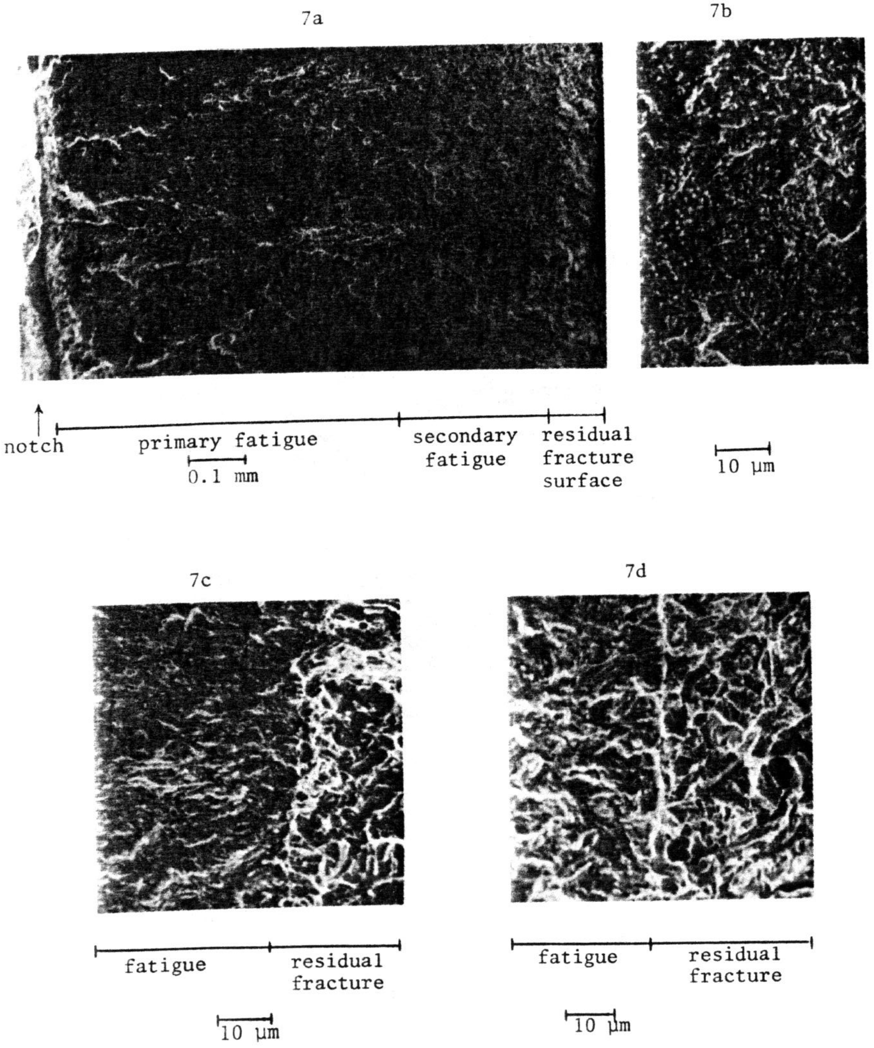

Figure 7

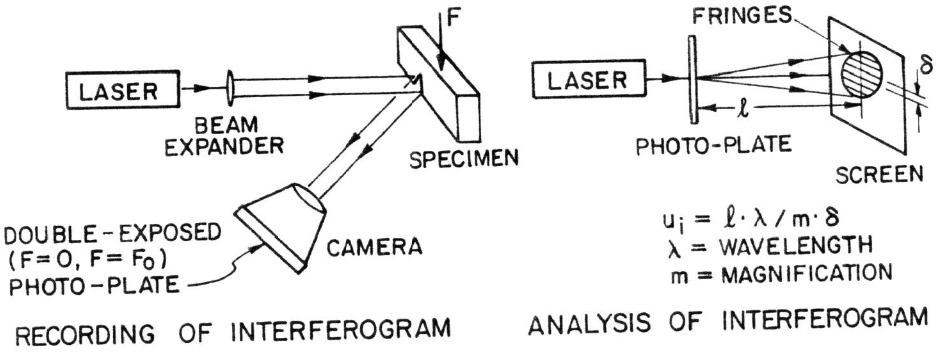

Figure 8