THE TEMPERATURE FIELD SURROUNDING THE FATIGUE CRACK TIP

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The work spent in the plastic zone in front of a fatigue crack is almost completely converted into heat. Shape and magnitude of the resulting temperature field are calculated.
The temperature field was measured in a sample of the steel "St 37" for a low crack growth rate.
The plastic work was determined directly from the mechanical hysteresis.
The computed values of the temperature and the shape of the temperatur field agree quite well with our measurements.

INTRODUCTION

If one plots load F vs. displacement v during one cycle of a fatigue test one obtains a hysteresis loop the area of which gives the mechanical work W spent in the specimen:

$$W = \oint F \, dv \tag{1}$$

One part of this work, A_F, is spent in friction in the specimen fixtures, the rest is used up as plastic work A_{pl} around the tip of the growing crack:

$$W = A_{pl} + A_F \tag{2}$$

where

$$A_{pl} = \int \oint \sigma \, d\varepsilon \, dV \tag{3}$$

The outer integral should, in principle, be extended over the total volume V of the specimen, but in realistic fatigue conditions it is limited to a "plastic zone" around the crack front that is small compared to the specimen size.

Since A_{pl} is converted almost entirely into heat (1), this plastic zone may be considered as a linear source yielding a heat flow

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$$\dot{Q} = A_{pl} \cdot f \tag{4}$$

where f is the frequency of loading.

The quasi-stationary temperature field generated by such a source has been computed and is shown in fig. 2 for a "center-crack specimen" as shown in fig. 1 where "top" and "bottom" of the specimen ($y = -Y$ and $y = +Y$) are kept at constant temperature. The numbers given on the lines of constant temperature are in units of

$$\dot{Q}/l\,\lambda \tag{5}$$

where l is the length of the crack front (thickness of the specimen) and λ the thermal conductivity. If a measured temperature field is compared to such pictures one obtaines immediately $\dot{Q}$ and, from equ.(4), A_{pl}.

EXPERIMENTAL PROCEDURE

Experiments according to equ.(1) were carried out on specimens as shown in fig. 3. Fig. 4 shows two typical hysteresis loops: they are very narrow and this puts a practical limit to the accuracy with which W can be determined.

Experiments according to equ.(4) were carried out with specimens as shown in fig. 1. The specimen surface was coated with liquid crystals showing various colours in the temperature range between 24.75°C and 25.4°C. During fatigue the specimens were kept insulated inside of a PMMA-container; top and bottom were kept at constant temperature. Fig. 5 shows a black and white photograph of the temperature field during testing. Here the white areas in the liquid crystal film correspond to the temperature intervall ranging from 25.0 to 25.4°C. All other temperature intervalls which in nature appear as different colours of the liquid crystals are indistinguishable and represented by the black areas of this photoprint.

The material used was St 37 with a yield strength of 200 MPa (analysis in weight%: C 0.16, Mn 0.35, Si 0.01, P 0.02, S 0.041, Cu 0.19, Cr 0.2, Ni 0.16, rest iron). The specimens were cut so that the crack surface would be perpendicular to the rolling direction.

RESULTS

Fig. 6 shows A_{pl}/l vs. stress-intensity factor range ΔK according to both methods. Here circles and triangles were determined from the load displacement loops and crosses from the temperature field. The points agree quite well for similar values of ΔK and confirm the relation

$$(\Delta K)^4 = C \cdot A_{pl}/l \tag{6}$$

In equ.(6) the constant C takes the value 4.10^{11} $[mm^{-6} \cdot N^3]$ as a result from the results plotted in Fig. 6. A_{pl} can be determined from equ.(1) only if A_F, the second term in equ.(2), can be neglected. In our experiment, this was true for

$$W/l > 0.2 \text{ J/m} \quad (7)$$

Conditions of this kind put a lower limit on the mechanical determination of A_{pl}/l which does not exist for thermal measurements.

REFERENCE

1. TAYLOR, G.I. and QUINNE, H., Proc. Roy. Soc. Series A, 143, 318 (1934)

This work was supported by the "Fonds zur Förderung der wissenschaftlichen Forschung, Projekt S 14/10".

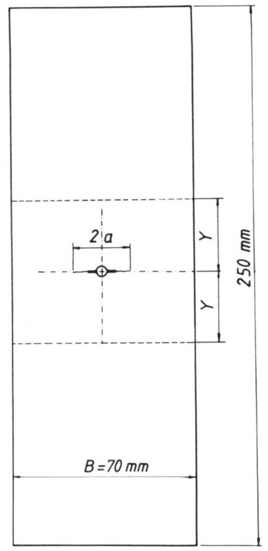

Figure 1 Center-crack specimen (thickness 5 mm)

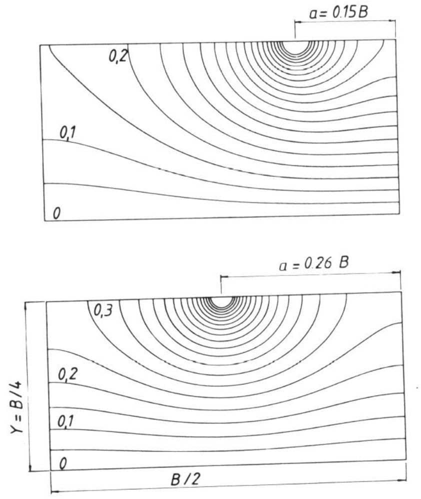

Figure 2 Computed temperature field in units of $\dot{Q}/l\lambda$

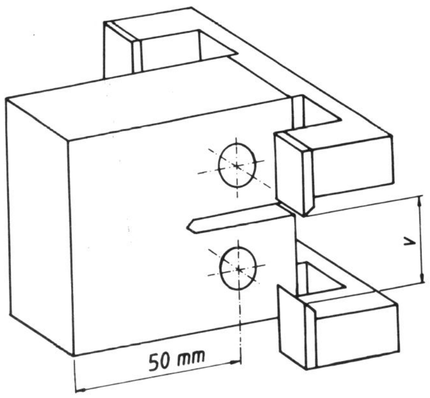

Figure 3 Experimental setup for deflection measurements

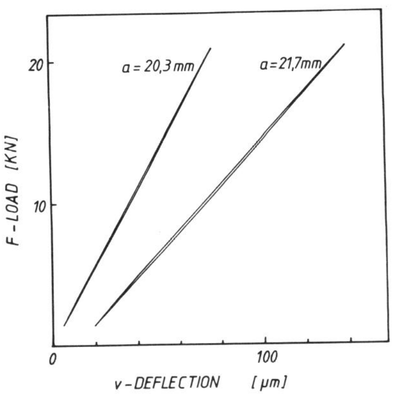

Figure 4 Typical load-deflection loops

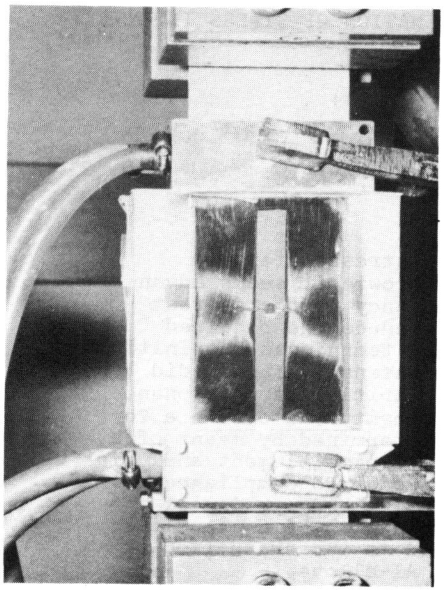

Figure 5 Experimental arrangement and typical temperature field

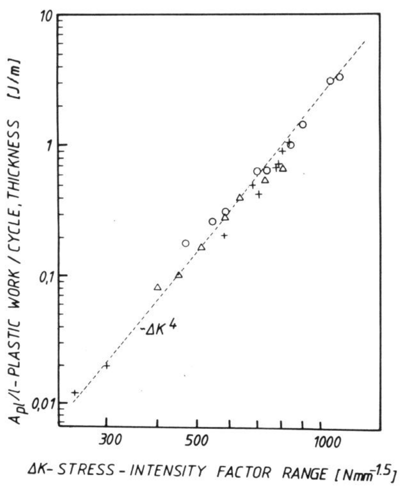

Figure 6 A_{pl}/l vs. ΔK for "St 37" (+: $R = 0.1$, O: $R = 0.1$, Δ: $R = 0.5$)