THE INFLUENCE OF A STATIC SHEAR LOAD ON SLOW MODE I FATIGUE CRACK GROWTH

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Fatigue crack propagation is studied under cyclic mode I plus superimposed static mode II loading with 12% Chromium steel at different R-ratios and crack lengths. At negative R-ratios, the influence of static mode II loading is more pronounced than at positive values. Enhanced crack growth rates are observed at negative and low positive R-ratios with crack lengths up to a defined value. This effect is mainly attributed to a reduction of fracture surface roughness by the compressive load components thus allowing an increase of the crack tip stress intensity by the mode II-shear component. For high R-ratios, long and short cracks grow slower than under pure mode I fatigue loading due to crack closure phenomena.

INTRODUCTION

In order to accurately predict the fatigue life of structure and machine parts which are subjected to low-amplitude, high frequency loading, it is essential to consider the near-threshold crack growth rate behavior in structural materials. Therefore this topic has received considerable attention (1). It is now recognized that near-threshold fatigue crack growth may be influenced by many sources like microstructural parameters, environmental effects etc. (2). All this knowledge originates from investigations which were performed in pure crack opening mode (mode 1) experiments. However, pre-cracked components are rather stressed in a combined mode (mode 1 + mode 2 or mode 3) than in pure mode 1. Some experience has been obtained on the fatigue crack growth behavior under combined loading conditions in the Paris regime ((3) and further literature cited there). But only few works exist on the influence of a combined load on the near-threshold fatigue crack growth behaviour(4-9), in spite of its great technical importance.

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It is the aim of this work to present studies on the influence of a static mode 2 load on mode 1-near-threshold fatigue crack growth in a structural steel used for steam-turbines (AISI 420, X20 Cr13) at different R-ratios.

EXPERIMENTAL PROCEDURE

Testing equipment

Near-threshold fatigue crack growth studies are very time-consuming due to long measuring times with high numbers of cycles. Therefore, the time and energy-saving ultrasonic fatigue method (loading frequency is 20 kHz) (10, 11) has been used for this work. Until recently it was not possible to perform combined loading tests with an ultrasound machine. Now, the fracture mechanics device (10) has been improved so that

- mean loads (tension or compression)
- conventional frequency loads
- and a constant torque load

may be superimposed to the high-frequency load of a specimen.

The principle of the machine is explained in detail in (12) and shortly described in the following.

A piezoelectric or magnetostrictive ultrasonic transducer is mounted to the crosshead of a conventional hydraulic machine with the upper coupling-piece. The specimen is attached to the other side of this coupling piece. The second end of the specimen is fixed to a lower coupling piece. These four parts are dimensioned such that they vibrate in resonance with the 20 kHz ultrasound. Nodal point of vibration and maximum of strain and stress are located in the center of specimen and coupling pieces. Via a disc which is fixed to the lower coupling piece a constant torque may be applied. Load cell and actuator are fixed to the lower end of the coupling piece. The actuator has a floating piston and therefore may be rotated during tension or compression loading with no mentionable friction. Thus, different kinds of load may be applied independently.
The machine is controlled by a computer, which supplies selected values for the loads generated by the ultrasound and the hydraulic machine. The actually performed ultrasonic displacement amplitudes are measured by an electrodynamic gauge and the static or conventional-frequency tension and compression loads are detected with the load cell. All these measured values may be stored and evaluated by the computer. The accuracy of load and strain control is at least equal to 1%.

Specimen shape

In order to superimpose a mode II to a mode I load tubular specimens with a radial crack may be used which are stressed in tension and compression axially and in mode II by a torsion load. This is shown in Fig.1 schematically. Fatigue crack growth studies were performed on steel (8) and mixed mode fracture studies on ceramics (13) with this specimen shape. In both cases radial narrow slots served as starter notches. However, this sort of starter notch suffers the following drawbacks for fatigue crack growth studies:

- Both notch tips (or both crack tips after crack initiation) must be observed during fatigue loading which brings about more instrumental and experimental costs.
- Machining of such notches usually needs special tools and much time.

These shortcomings are reduced if the starter notch is produced as a one-sided notched hole. Machining is easier and a fatigue crack originates and grows only from the one notched part of the hole. Specimen and starter-notch shape are shown in Fig.2.

Testing Material

The material employed in this investigation was 13% Chromium steel (Ferritic X20 Cr13 steel: in wt%: 0.19 C, 0.42 Si, 0.39 Mn, 0.028 P, 0.005 S, 13 Cr; austenitized at 940°C 1 hour, oil quenched and tempered for 1 hour at 650°C) with following mechanical properties:

$R_{p0.2}$ = 550 MPa, R_m = 870 MPa

Stress intensity factor calculation

Stress intensity factors K_I and K_{II} were calculated according to Erdogan and Ratwani (14, 15) with

$$K_I = \sigma \sqrt{\pi a}\ Y$$

$$K_{II} = \tau \sqrt{\pi a}\ Y$$

(σ = tensile stress, τ = shear stress, a = crack length including notch depth, Y = geometry factor). The geometry factor was determined according to Tada et al. (16) with a fitted polynomial function. The starter-notch shape influence was taken into account according to the procedure of Schijve (16). In the following, c stands for the crack length without notch depth, d, i.e. a = c + d. Ultrasonic loading was of push-pull type (R = -1) as long as no static mode I load was superimposed.

The ΔK_I or K_{max} values for cyclic loading were obtained as:

$$K_{max} = (\Delta K_I/2) = \sigma_c \sqrt{\pi a} \quad Y$$

where σ_c is determined according to

$$\sigma_c = \frac{\pi E}{l_v} \cdot A \cdot Z$$

with E = Young's modulus, A = displacement amplitude, l_v = resonance length of specimen and Z = factor, which takes into account the changing specimen compliance due to crack extension.

It is pointed out that tubular specimens of course are likewise appropriate to perform mode I crack growth studies without superimposed mode II load. Thus it is possible to compare mode I and mode I + superimposed mode II experiments directly with the same specimen. For superposition of mode III loads cylindrical bars instead of tubular specimens are used which are likewise appropriate for pure mode I tests. Another advantage of using round or cylindrical specimens is that it is sometimes easier to machine these shapes than rectangular ones.

RESULTS AND DISCUSSION

Fig.3 shows the influence of R-ratio and crack length on mode I fatigue crack growth with a static mode II load superimposed.

The ΔK_I values were chosen such that identical crack growth rates resulted for all four tested R-ratios (R = -1, -0.5, 0, +0.5) as long as no mode II load was superimposed. Following nominal ΔK_I and K_{max} - values (in $MPa\sqrt{m}$) were used:

for R = -1 : ΔK_I = 12 , K_{max} = 6
R = -0.5: ΔK_I = 9.8, K_{max} = 6.5
R = 0 : ΔK_I = 7 , K_{max} = 7
R = +0.5: ΔK_I = 4.7, K_{max} = 9.4

The resulting mode I fatigue crack growth rate was 7.10^{-10} m/cycle for all four R-ratios. It is characterized by the dash-dotted horizontal line in Fig.3. The constant crack growth rate shows that the effective ΔK_I value (nominated ΔK_{Ieff} in Fig.3) was identical for all four R-ratios.

For the experiments with superimposed mode II loads, the same above-mentioned constant nominal ΔK_I and K_{max} values were chosen in order to have identical initial testing conditions. K_{II} was kept constant during the tests; i.e. K_{II} was 12 MPa$\sqrt{m}$.

The resulting crack growth rates in Fig.3 show that for a relatively short *) crack of 0.5 mm, higher crack growth rates than without superimposed mode II load result for all tested R-ratios except for R = +0.5. Approximately the same is found for a crack with a length of c = 2 mm, however, the point of intersection of the K_{II} = 0 with the K_{II} = 12 MPa$\sqrt{m}$ curve is at approximately R = +0.3 instead of R ~ 0.5. This shows that crack growth is retarded at R-ratios higher than +0.3 when a static mode II load is superimposed.

At a crack length of 3.5 mm or longer (5 mm), reduced crack growth rates are found for all R-ratios between -1 and +0.5.

Fig.3 shows in addition that the crack growth rate for combined loading is varying much more for negative than for positive R-ratios which points to a pronounced influence of compressive components.

The results of Fig.3 demonstrate that superposition of static mode II to cyclic mode I loading causes increased crack growth rates for relatively short cracks at low and negative stress ratios and reduced crack growth rates for long cracks in all loading conditions.

These results may be explained by the assumption of two opposing mechanisms. First, superposition of mode II loading obviously increases the resulting effective stress intensity by generating a higher crack tip displacement, thus accelerating crack advance. With increasing crack length however, this effect is opposed by another mechanism which is sliding fracture surface interference. As the fracture surface area increases with growing crack, friction and mutual support of the fracture surface asperities increase likewise, thus decreasing the effective stress intensity value at the crack tip.
At first sight one might expect that high positive R-ratios (tensile loads) reduce the effect of sliding fracture surface interference and therefore favour increased crack growth rates under superimposed mode II loads rather than low or negative R-ratios. However, the opposite is shown in Fig.3. To interpret this result, it is assumed that the applied static tensile load obviously was not high enough in our tests to open the crack sufficiently, so that the sliding fracture surface interference is completely removed (slightly reduced crack growth rates for

*) For the purposes of this work "relatively short" cracks are longer than "short" cracks in the usual sense; i.e. they are long enough to allow the concepts of LEFM to characterize their growth behaviour.

all crack lengths at R = +0.5). But if compressive parts of cycling become effective (at R = -1 and less pronounced at R = 0), the asperities are flattened so that the relative mismatch between them is removed or reduced such that friction, abrasion and mutual support of the asperities cannot be (fully) effective any longer.

Under mode I loading at R = 0, only limited compressive stresses are built up by surface asperities; compressive stresses are smaller than at R = -1; therefore, a constant lower crack growth rate is obtained for shorter crack lengths at R = 0 than at R = -1.

A case which occurs in practice quite often is shown in Fig.4. The nominal ΔK_I values were kept constant (ΔK_{Inom} = 7 MPa$\sqrt{m}$) instead of the initial ΔK_{Ieff} in the experiments with R-ratios of -1, -0.5, 0 and +0.5. In addition, K_{II} was kept constant at 12 MPa$\sqrt{m}$.

The reference line for $K_{II} = 0$ is characterized by a dash-dotted line in Fig.4. It shows that higher crack growth rates result for higher mean loads than for low and zero mean loads, with a constant nominal ΔK_I of 7 MPa$\sqrt{m}$ and $K_{II} = 0$ as parameter.

If a static mode II load (K_{II} = 12 MPa$\sqrt{m}$) is superimposed, slower crack growth rates result at a crack length of 5 mm for all tested R-ratios. At R-ratios below -0.5 even crack arrest could be detected (The threshold crack growth rate is approximately 5.10^{-11} m/cycle, which is shown as shaded area in Fig.4). However, for a crack of only 0.5 mm length, increased crack growth rates result at R-ratios between -1 and +0.3. Even crack growth occurs where the 5 mm long crack has stopped already.

CONCLUSIONS

Superposition of static mode II loads on mode I fatigue loads may accelerate or retard fatigue crack propagation. What will actually occur depends on mean load and crack length.

At negative R-ratios, the influence of a superimposed static mode II load on mode I fatigue crack propagation is more pronounced than at positive R-ratios.

Long cracks (typically longer than 3 mm in this work) are retarded if a static mode II load is superimposed at all tested R-ratios between -1 and +0.5. Up to a defined length (approximately 2 mm in this work) cracks grow faster under superimposed mode II loads at negative, zero and low positive R-ratios.

For practical purposes, especially the possibility of crack growth acceleration under superimposed mode II loads should be kept in mind. The same is true for cases, where nominally pure mode I loads are applied, but where shear components become effective owing to some secondary - usually undefined - mechanisms.

ACKNOWLEDGEMENT

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REFERENCES

(1) Davidson,D.L. and Suresh,S., "Fatigue Crack Growth Threshold Concepts", Proceedings of the Metallurgical Society of AIME, Pennsylvania, USA, 1983

(2) Ritchie,R.O., Inter. Metals Reviews, Nos.5 and 6, 1979, p.205

(3) Miller,J.K. and Brown,M.W., ASTM STP 853, 1985

(4) Tanaka,K., Eng. Frac. Mech., Vol.6, No.3 , 1974, pp. 493-507

(5) Sih,G.C. and Barthelemy,B.M., Eng. Frac. Mech. Vol. 13, No. 3, 1980, p.439

(6) Pook,L.P., Int. J. of Fracture, Vol.13, No.6, 1977, p.867

(7) Gao,H., Brown,M.W. and Miller,K.J., Fatigue of Eng. Mat. and Struc., Vol.5, No.1, 1982, p.1

(8) Stanzl,S.E., Czegley,M., Mayer,H.R. and Tschegg,E.K., ASTM STP, 1987, in press

(9) Otsuka,A., Mori,K., Ohshima and Tsuy ama,S., ICF 5, Vol.4, 1981, p.1851

(10) Mitsche,R. and Stanzl,S.E. and Burkert,D., Wiss. Film, Vol.14, 1973, p.3

(11) Stanzl,S.E. and Tschegg,E.K., Metal Science, April 1980, p.137

(12) Tschegg,E.K., Czegley,M., Mayer,H.R. and Stanzl,S.E., J. Physics E, submitted 1987

(13) Petrovic,J., J. of Amer. Ceramic Society, Vol.68, No.6, 1985, p.384

(14) Erdogan,F. and Ratwani,M., Int. J. of Frac. Mech., Vol.6, No.4, 1970, p.379

(15) Erdogan,F. and Ratwani,M., Int. J. of Frac. Mech., Vol.8, No.8, 1972, p.87

(16) Tada,H., Paris,P.C. and Irwin,G.R., The Stress Analysis of Cracks Handbook, Del. Research Coop., Hellertown, P.A., 1973

(17) Schijve,J., Stress Intensity Factors of Hole Edge Cracks. Comparison between One Crack and Two Symmetric Cracks, Int. J. Frac., Vol.23 (1983), pp.R111-R115

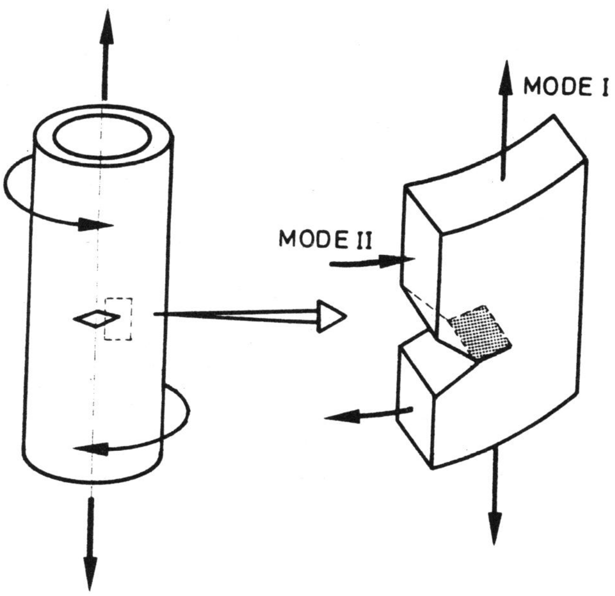

Figure 1 Specimen for high-frequency cyclic mode I plus superimposed static mode II loading

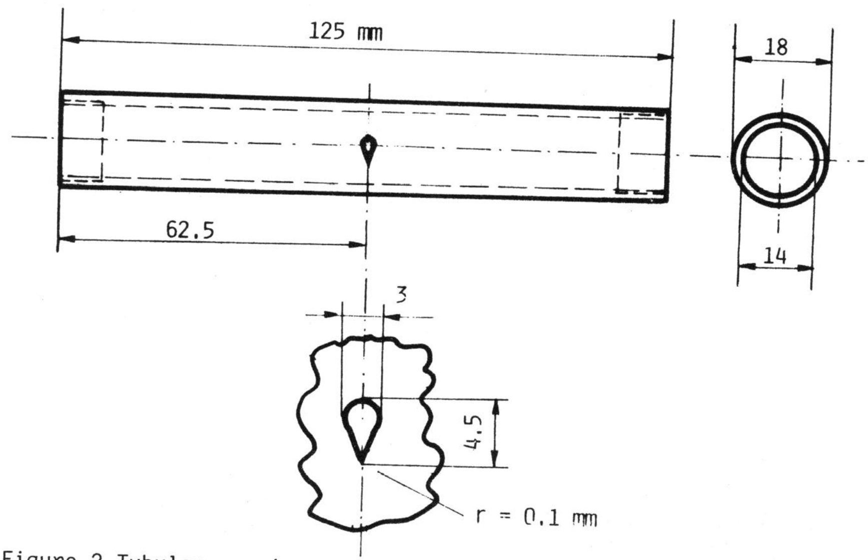

Figure 2 Tubular specimen with starter notch for cyclic mode I plus superimposed static mode II loading

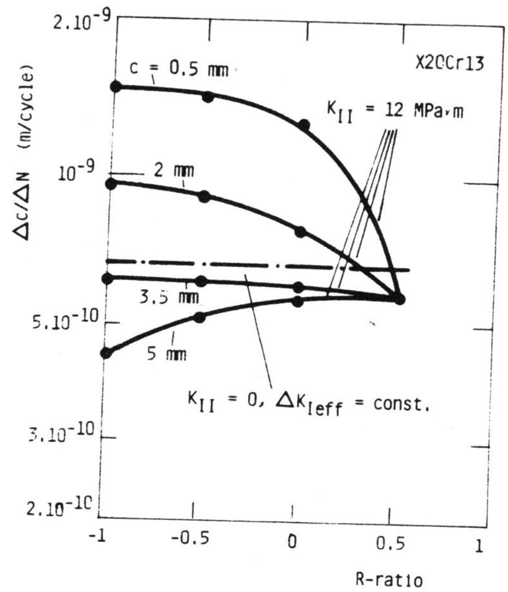

Figure 3 Crack length (c) and R-ratio influence on crack growth under constant K_{II} plus initially constant effective ΔK_{Ieff}

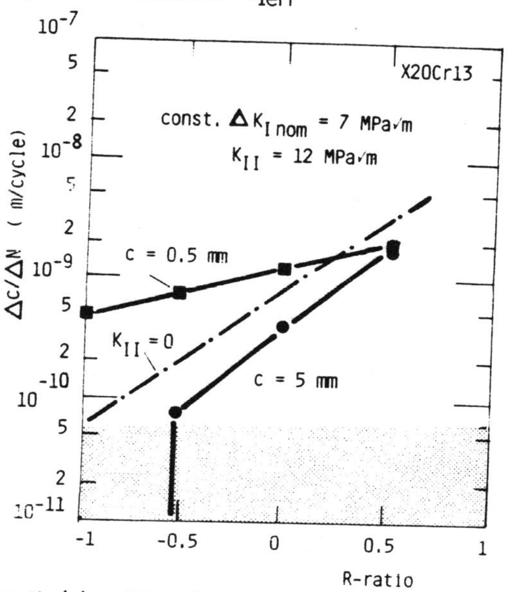

Figure 4 Crack length (c) and R-ratio influence on crack growth under constant K_{II} plus constant nominal ΔK_{Inom}