EFFECT OF TENSION-COMPRESSIVE CYCLING ON FATIGUE CRACK GROWTH

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ABSTRACT

The influence of tension-compressive cycling on fatigue crack growth was investigated at ambient temperature. Fatigue crack growth tests were performed on compact tension specimens of different quenched and tempered steels using a frequency of 10 Hz applying stress ratio R varying from +0,5 to -1. The results showed that under plane strain conditions and cyclic tensile compressive loads only the tensile component of the load produces crack growth, whereas the compressive component causes no crack propagation.

KEYWORDS

Fatigue crack growth; tension-compressive cycling; plane strain conditions; quenched and tempered steels.

INTRODUCTION

The crack growth rate behaviour under cyclic loads and plane strain conditions has so far been predominantly analysed only for loads within the stress intensity factor range in the tension region, i.e. at stress ratios $R > 0$. During actual service, many components are, however, subjected to both cyclic tensile stress and to cyclic compressive stress, i.e. stress ratios $R < 0$. Figure 1 shows a schematic representation of the stress cycles. In this connection, the question arises as to which cyclic stress intensity factor should be used for calculating the crack growth rate at $R < 0$. It is known from the literature and own tests that the crack growth rate changes only insignificantly within the range of alternating tensile stress up to $R = +0,5$ as compared to the results of tests normally conducted at $R = 0$ to $0,1$ (Wiemann, 1977).

However, there are very few publications relating to the effect of a combined tensile-compressive load on the crack growth rate.

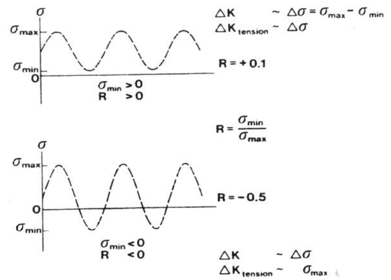

Fig. 1. Load Cycle Diagram (Schematic)

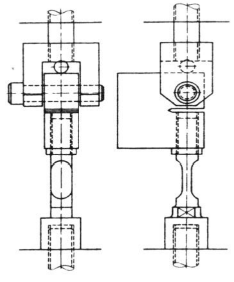

Fig. 2. Test Equipment for Fatigue Crack Growth Measurements Under Tension-Compression Cycling

In addition, these are hardly comparable due to the differences in the materials (structural steels, quenched and tempered steels, aluminium alloys) and specimens (plate, SEN, CT specimens) analysed. In spite of the great differences in the test conditions, it can, however, be generalised that an effect of compressive stresses on the crack growth rate is to be expected for plate specimens with centre and edge notch which are very thin and thus exhibit plane stress conditions (Crooker, 1971; Hsu, 1979; Maddox, 1975; Ohta, 1978; Saal, 1972; Schütz, Wiemann, 1977). Gamble and Paris (1976), using specimens largely satisfying the plane strain criterion, have shown that there is no effect on the crack growth at room temperature. However, at a temperature of 480°C, the crack growth rate behaviour of the same specimens is effected by compressive stresses.

Skelton and Haigh (1978) have arrived at similar results. But considering the high temperatures, it must be assumed that the specimens were subjected to the loads in a largely plane strain condition.

For heavy machinery and large apparatus components, such as shafts, turbine discs or thick-walled pressure vessels, largely plane strain conditions can be assumed. The object of the present work was to analyse the effect of cyclic tension-compression loads under this condition on the crack growth rate behaviour.

EXPERIMENTAL DETAILS

Material for this investigation was obtained from the interior of shafts and discs manufactured from 1 % CrMoNiV, 12 % CrMoV and 3,5 % NiCrMoV quenched and tempered steels. The chemical compositions and mechanical properties are presented in the attached tables.

TABLE 1 Chemical Composition in %

Specimen No.	Material	C	Si	Mn	P	S	Cr	Mo	Ni	V
1	26 NiCrMoV 14 5	.28	.19	.26	.006	.007	1.60	.39	3.64	.10
2	30 CrMoNiV 5 11	.33	.20	1.22	.006	.011	1.04	1.17	.94	.31
3	X 22 CrMoV 12 1	.21	.33	.73	.012	.003	11.90	1.04	.54	.30

TABLE 2 Component Description and Mechanical Properties

Specimen No.	Component	Leading Dimension mm	Specimen Location	$R_{p0,2}$	R_m	A	Z	FATT	NDTI
				MPa		%	%	°C	°C
1	Disc	Ø 2925 x 760	Hub Centre	840	1000	16	51	-35	-40
2	Shaft	Ø 1235x11500	Axial Trepan	630	840	20	55	+110	-65
3	Shaft	Ø 1150x4305	Axial Trepan	660	825	19	50	+45	+10

Tests were conducted on CT2 specimens (50 mm thickness). The specimens were taken from the components for loading in tangential direction and crack propagation in radial direction. Tests were conducted in a closed loop, hydraulically activated test machine, using a frequency of 10 Hz at room temperature. Data were obtained at stress ratios of R = +0.5, R = +0.1, R = -0.5 and R = -1, using two specimens for each stress ratio. To avoid a discontinuity in the zero crossing of the load-time function, the gripping device and the specimen had to be modified as shown in Fig. 2. An additional steel ball was braced between the holder and the specimen in order to avoid sudden changes in the stress on zero crossing of the load due to an abrupt loss of a clearance.

Crack growth rate was measured by the AC potential method (600 Hz). Additional reference marks for optical crack length measurements were provided on the lateral faces of the specimens for the purpose of identifying any effect of the compressive load on the electric potential. Crack growth constants m and c were determined with the aid of the Paris equation.

EXPERIMENTAL RESULTS

Effect of Specimen Gripping on Crack Growth Rate Behaviour

To check the effect of specimen gripping, the results of standard CT2 specimens were compared with those obtained with the newly developed gripping device and modified CT2 specimens (under cyclic tensile stress intensity at $R = +0.1$). The data in Fig. 3 indicate no effect of any additionally arising bending stresses due to the "rigid" attachment on the crack growth rate.

Effect of Tensile-Compressive Load on Electric Potential

Crack lengths determined by means of the AC potential method and by optical measurement at different stress ratios are compared in Fig. 4.

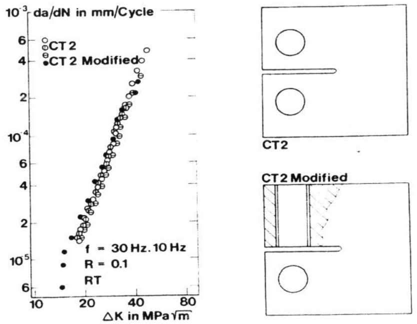

Fig. 3. Fatigue Crack Growth Measurement With **Different CT2-Specimens** (1 % CrMoNiV-Steel)

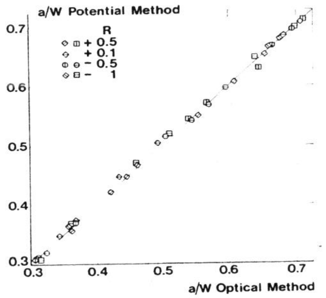

Fig. 4. Comparison of Different Crack Length Measurement Procedures on Example of 1 % CrMoNiV-Steel

Slight deviations are revealed, amounting to approximately ± 1 % for the average of the a/w values and to a maximum of ± 2.5 %. These deviations are most probably to be attributed to the limited accuracy obtainable in determining the crack length by means of the optical method. Note that the crack front was largely straightline in all cases.

Effect of Stress Ratio R on Crack Growth Rate Behaviour

The various experimental data sets obtained for 1 % CrMoNiV steel are compared in Fig. 5. For stress ratios of $R = +0.5$ and $R = +0.1$, the stress intensity factor ΔK was calculated for the full range of stress $\Delta\sigma$ (see also Fig. 1). For stress ratios of $R = -0.5$ and $R = -1$, the stress intensity factor was calculated both for the full range of stress $\Delta\sigma$ and for the tensile load component only, i.e. σ_{max}. Hence, for each crack growth rate, a data set is obtained for the stress intensity factors ΔK and $\Delta K_{tension}$. Taking into account the full range of stress intensity ΔK, the test results appear to indicate an improvement in the crack growth rate behaviour with increasing compressive load component.

If, however, only the tensile component $\Delta K_{tension}$ is considered, there is hardly any change in the crack growth rate as compared to the "normal" cyclic tensile stress intensity ($R = +0.1$).

A similar behaviour was observed also on the two other materials. In Fig. 6 the results are plotted in the form of mean value curves. A slight decrease in the crack growth rate is observed for all three materials even with increasing compressive component, i.e. with decreasing stress ratio.

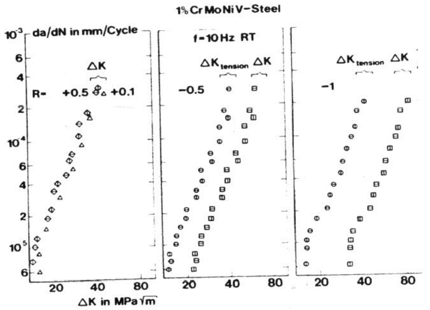

Fig. 5. Influence of Stress Ratio on Fatigue Crack Growth

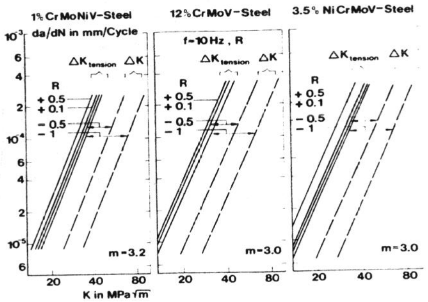

Fig. 6. Influence of Stress Ratio on Fatigue Crack Growth

This can be visualised by determining constants c and m according to the Paris equation and plotting them as a function of the stress ratio as shown in Fig. 7.

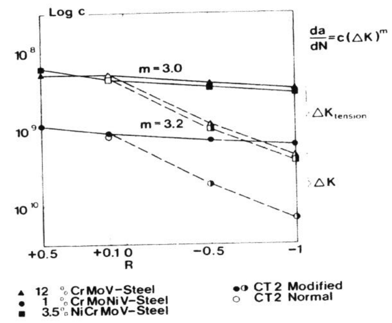

Fig. 7. Influence of Stress Ratio on Fatigue Crack Growth Constants

Note that the different stress ratios have no significant effect on the slopes of the crack growth characteristics. For the stress ratios analysed, m values of 3.0 and 3.2 were obtained.

From the unimportant change in the crack growth rate behaviour with increasing compressive component it can be derived that under plane strain conditions the crack is closed at the zero crossing of the load at the latest, with the compressive stresses developing in the vicinity of the crack tip not contributing to crack growth. Further crack growth only occurs as a result of the tensile stresses developing at the instant of the next zero crossing. From the fact that the crack growth rate decreases with increasing compressive component it must probably be concluded that, dependent on R, crack closing occurs already before the zero crossing of the stress, with residual stresses of varying magnitude becoming effective due to the plastic deformation at the crack tip. If the calculation of ΔK would only be based on that fraction of the range of stress at which the crack is open, it is to be assumed that there will be even less spread between all results. The investigations so far conducted permit no assessment of the instants when crack closing or crack opening is initiated. Supporting data are to be derived from photoelastic investigations.

It is known from tests conducted on specimens with residual stresses that these affect the mechanism of crack propagation. On specimens with different residual stresses, compressive residual stresses delay the crack growth, whereas residual tensile stresses cause an increase in the propagation rate. The specimens tested for the present work were free of residual stresses and exhibited a straightline crack propagation pattern. Any residual stresses due to manufacturing must as a matter of principle be considered in the design calculations.

CONCLUSIONS

Based on the results available, it can be concluded that under plane strain conditions and cyclic tensile-compressive loads only the tensile component of the load produces crack growth, whereas the compressive component causes no crack propagation.

The findings permit a realistic assessment of cracks in large components subjected to cyclic tension-compression loads, i.e. an excessively conservative approach can be avoided.

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