PREDICTION OF PART-THROUGH CRACK GROWTH IN STRUCTURAL COMPONENTS

A.Ya.Krasowsky*, V.A.Vainshtok* and I.V.Varfolomeyev*

The problem is considered of transforming fatigue crack growth properties from standard specimens to components containing part-through flaws. The analysis of fatigue crack growth criteria is based on test results of surface- and corner-cracked plates made of pressure vessel steel. The effective stress intensity factor range is found to be preferable as a fatigue crack growth criterion when predicting the part-through crack growth under cyclic loading. Predicted crack shape variation is compared with experimenal data.

INTRODUCTION

The material fatigue crack growth properties are usually determined on standard specimens with through-the-thickness cracks for which the stress state is characterized by a single fracture mechanics parameter. Various approaches are used for transforming the fatigue crack growth data from standard specimens to structural components with part-through flaws (Nagai et al (1), Kawahara and Kurihara (2), Cruse and Besuner (3), Müller et al (4)). Within the frameworks of the linear elastic fracture mechanics, the ranges of the local (ΔK), averaged ($\Delta \bar{K}$) and effective (ΔK_e) values of the stress intensity factor are discussed in (4) as surface crack growth criteria. Meanwhile, the known investigations do not allow one to determine recommendations as to the choice of part-through crack growth criteria under cyclic loading (see, e.g., (4)). In the present paper, basing on the original experimental data, the authors performed a comparative analysis of the applicability of

---

* Institute for Problems of Strength, Academy of Sciences of the Ukr.SSR, Kiev, USSR

the ΔK, $\Delta \bar{K}$ and ΔK_e values for predicting surface and corner crack growth under cyclic loading.

EXPERIMENTAL PROGRAM AND RESULTS

Material and Specimens

The part-through flaw propagation was studied on plates of a length L = 220 mm, a width 2W = 116 mm and a thickness B = 30 mm made of pressure vessel steel 15Kh2MFA ($\sigma_{0.2}$ = 584 MPa, σ_u = 700 MPa, δ = 21%, ψ = 74.6%). The specimens with a single surface crack and the specimens with two corner cracks originating at opposite edges of the mid plate section were tested. To initiate part-through flaws, notches of 0.5 to 5 mm deep were introduced by using the electro-spark technique. The beach mark method was applied for monitoring the crack geometry. Basic fatigue crack growth properties of the material were determined on standard single-edge-notch specimens sizing 210x50x25 mm^3. The experiments were carried out in four-point bending fatigue at the frequency of 10 Hz and the stress ratio R = 0.32, in air, at room temperature. The value of fatigue crack growth rate in testing varied within the Paris region of the fatigue crack growth curve. The plates with part-through cracks were tested in the nominal stress variation range of σ_{nom} = (0.38...0.9) $\sigma_{0.2}$.

Part-Through Crack Growth Model and Criteria

It was observed from the specimen fracture surfaces that the real surface or corner crack front is well approximated by a semi-ellipse or a quarter-ellipse which fact was also noted by Müller et al (4), Pierce and Shannon (5), Truchon and Lieurade (6), Hodulak et al (7) and other authors. Thus, the analysis of part-through crack development can be performed basing on a crack front model with two degrees of freedom:

$$da/dN = b(\Delta K_A^*)^n \ , \quad dc/dN = b(\Delta K_C^*)^n \qquad (1)$$

where a and c are the ellipse half-axes (a is the crack depth), A and C are the vertices of the corresponding half-axes, ΔK^* is the fracture mechanics parameter taken as the fatigue crack growth criterion, b and n are the empirical constants determined from the test results for standard specimens.

The local, averaged and effective stress intensity factor ranges were considered as the ΔK^* value. The weight function method (Vainshtok and Varfolomeyev (8)) was applied for the local stress intensity factor computation. The $\bar{K}_a$ and $\bar{K}_c$ values were calculated through an average energy release rate according to the approach by Cruse and Besuner (3).

In order to take into account the difference in physical and mechanical properties of the material and the variation in strain constraint along the crack front, a criterion of the effective stress intansity factor range is normally used (see, e.g., Müller et al (4), Hodulak et al (7), Newman and Raju (9), Jolles and Tortoriello (10), Fleck et al (11)). Let us introduce the following definition of the ΔK_e value:

$$\Delta K_{e,a} = \tau_a \Delta K_a \quad , \quad \Delta K_{e.c} = \tau_c \Delta K_c \tag{2}$$

where the coefficients τ_a and τ_c are determined on the basis of experimental data from the condition that through-the-thickness and part-through crack growth rates have to coincide with equal values of ΔK_e.

We do not aim at studying the physical nature of the ΔK_e value which can be related to features of the material macro- (Hodulak et al (7)) and microfracture (Letunov et al (12)) at different points of the crack front. From our viewpoint, the ΔK_e definition in the form of eqs (2) is convenient for analyzing the conditions of transforming fatigue crack growth properties from standard specimens to structures.

Fatigue Crack Growth Data

Surface cracks. Figure 1 presents surface crack growth rates da/dN (dark symbols) and dc/dN (light symbols) plotted vs the ΔK and $\Delta \bar{K}$ values. The dashed and solid lines represent a scatter band of experimental results for standard specimens and their appoximation in the range of ΔK = (20...50) MPa$\sqrt{m}$ by the Paris formula

$$dl/dN = b(\Delta K)^n \quad , \text{ m/cycle} \tag{3}$$

where l is the edge crack length, $b = 2.96 \cdot 10^{-11}$, n = 2.54 . Different points in Fig.1 correspond to five specimens tested.

The analysis of the results in Fig.1 shows that if the averaged stress intensity factor is used as the fatigue crack growth criterion, the majority of experimental points are beyond the scatter band of the standard specimen data; moreover, the da/dN,dc/dN vs $\Delta \bar{K}$ appoximation curve and diagram (3) have appreciably different slopes. The dc/dN vs ΔK_C data virtually coincide with the standard specimen test results. At the same time, with similar stress intensity factor ranges the surface crack growth in the direction of its depth occurs with higher velocity than in the direcion of its length. The same conclusion was also made by the authors of (4),(7),(9)-(12). Thus, the ΔK-criterion does not take into account the difference in surface crack growth rates da/dN and dc/dN with equal values of ΔK_A and ΔK_C.

If the effective stress intensity factor range is used as fatigue crack growth criterion, the coefficients γ_A and γ_C have to be determined. Basing on the least-square technique, the magnitudes of γ_A and γ_C were calculated for each specimen tested and the average values are $\gamma_A = 1.1$, $\gamma_C = 1$. Note a fair agreement of the ratio $\gamma_A/\gamma_C = 1.1$ obtained in the present paper with the data of (9)-(11).

Corner cracks. If the criterion of the averaged stress intensity factor range is applied, experimental results for corner-cracked plates don't agree well with the fatigue crack growth data of standard specimens. At the same time with the equal values of the local stress intensity factor for corner and through cracks, fatigue crack growth rates da/dN, dc/dN and dl/dN coincide within the scatter band, and we have $\gamma_A = \gamma_C = 1$. In general, the values of γ_A and γ_C may differ from unity (for instance, when the thickness of a standard specimen differs essentially from the one for a corner-cracked plate). In this case the use of the ΔK_e criterion may be recommended with $\gamma_A = \gamma_C$.

PREDICTION OF CRACK SHAPE DEVELOPMENT

Having eliminated parameter N from eqs (1), the equation may be obtained

$$d(a/c)/d(a/B) = (a/c)/(a/B)\ [1-(a/c)(\Delta K_C^*/\Delta K_A^*)^n] \qquad (4)$$

which describes the change in a part-elliptical crack shape under cyclic loading. The known experimental data (see (2),(4)-(7),(9),(10)) reveal the fact that irrespective of the initial configuration defined by the parameters $(a/b)_o$ and $(a/h)_o$ the crack shape tends to a stable state during fatigue growth. The crack stable shape can be defined analytically as an asymptotic curve for solutions of eq (4) under various initial conditions.

In Figs.2 and 3 the experimental data of the present work, which describe the surface and corner crack shape variation in cyclic bending, are compared with stable shapes obtained by solving equation (4) with the use of the local, averaged and effective stress intensity factor ranges as ΔK^{*}. It is evident that the use of the ΔK_e criterion (or ΔK for a corner crack) gives the best results when predicting the crack shape. In this case, the experimental data actually coincide with the calculated curve up to $a/B = 0.6$. In the case when $\Delta \bar{K}$ was used as the fatigue crack growth criterion, the calculated value of the crack shape parameter turned out to be overestimated, while in the case when ΔK was used (for a surface crack), it was somewhat underestimated.

Note, that similar conclusions concerning the applicability of various fracture mechanics parameters to predicting part-through crack growth under cyclic loading have been made above when analysing fatigue crack growth data.

CONCLUSION

With the use of two-parametric crack front model and the ΔK_e value as fatigue crack growth criterion, an accurate prediction of part-through crack growth under cyclic loading was obtained. The magnitude of τ_A/τ_C, which characterizes the ratio of the part-through crack growth rates in the depth and length directions with $\Delta K_A = \Delta K_C$, is equal to 1.1 for a surface crack and to 1 for a corner crack. In the present paper τ_C was obtained equal to 1 if the thicknesses of a standard specimen and the part-through-cracked plate are close.

SYMBOLS USED

$\Delta K, \Delta \bar{K}, \Delta K_e$ = ranges of the local, averaged and effective stress intensity factor, (MPa$\sqrt{m}$)

K_A, K_C = stress intesity factor values at the points A and C of the crack front (MPa$\sqrt{m}$)

ΔK^{*} = fatigue crack growth criterion (MPa$\sqrt{m}$)

l = through crack size (m)

n, b = empirical constants in the Paris formula

τ_A, τ_C = constants in expressions of ΔK_e

REFERENCES

(1) Nagai,A., Toyosada,M. and Okamoto,T., Engng Fracture Mech., Vol.7, 1975, pp.481-490.

(2) Kawahara,M. and Kurihara,M., Advances in Fracture Research, ICF4, Vol.2, 1977, pp.1361-1373.

(3) Cruse,T.A. and Besuner,P.M., J. Aircraft, Vol.12, 1975, pp.369-375.

(4) Müller,H.M., Müller,S., Munz,D. and Neumann,J., ASTM STP 905, 1986, pp.625-643.

(5) Pierce,W.S. and Shannon,J.L.,Jr., J. Testing and Eval., Vol.6, 1978, pp.183-188.

(6) Truchon,M. and Lieurade,H.P., Advances in Fracture Research, ICF5, Vol.1, 1981, pp.31-39.

(7) Hodulak,L., Kordisch,H., Kunzelmann,A. and Sommer,E., ASTM STP 677, 1979, pp.399-410.

(8) Vainshtok,V.A. and Varfolomeyev,I.V., Int. J. Fracture, Vol.38, 1988, pp.R71-R74.

(9) Newman,J.C.,Jr. and Raju,I.S., Advances in Fracture Research, ICF6, Vol.3, 1984, pp.1597-1608.

(10) Jolles,M. and Tortoriello,V., ASTM STP 791, 1983, pp.I-297-I-307.

(11) Fleck,N.A., Smith,I.F.C. and Smith,R.A., Fatigue Engng Mater. Struct., Vol.6, 1983, pp.225-239.

(12) Letunov,V.I., Kramarenko,I.V., Shul'ginov,B.S. and Vainshtok,V.A., Strength of Materials, Vol.18, 1986, pp.13-16.

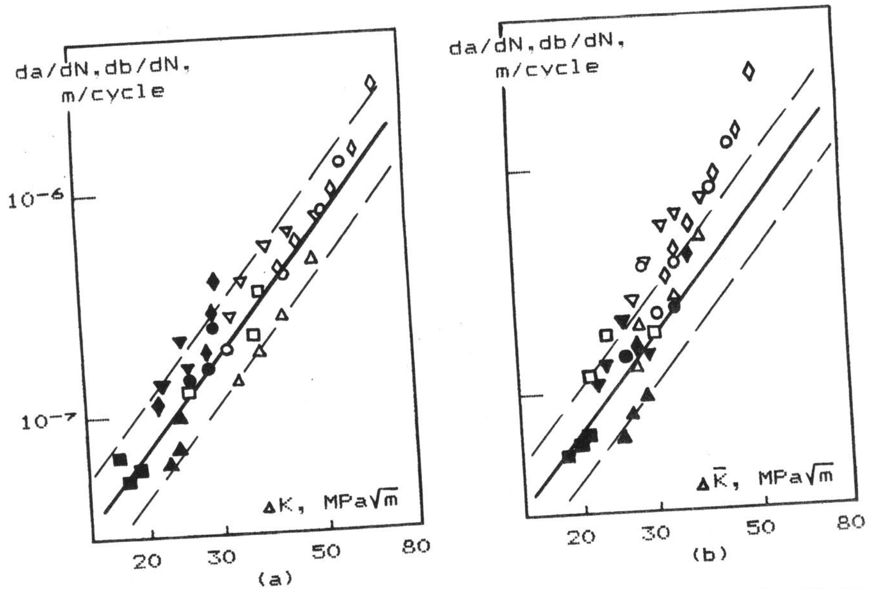

Figure 1 Surface crack growth rates da/dN and db/dN vs the ΔK (a) and $\Delta\bar{K}$ (b) values

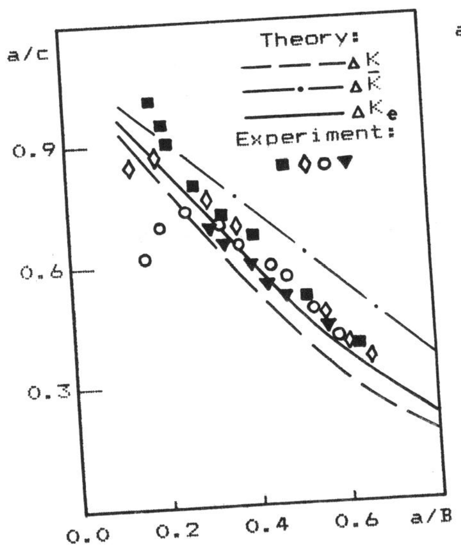

Figure 2 Surface crack shape variation

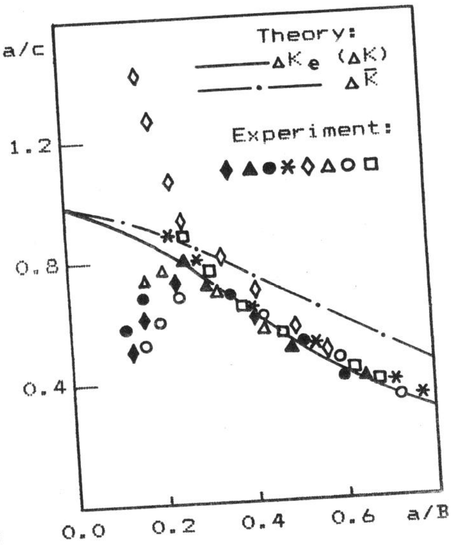

Figure 3 Corner crack shape variation