EFFECT OF STRESS RATIO AND MAXIMUM STRESS ON CRACK CLOSURE

K. Anandan*, P. K. Dash* and K. K. Brahma*

Small scale yielding (SSY) limitation, in terms of maximum stress S_{max} to yield stress σ_{ys} ratio, for application of Linear Elastic Fracture Mechanics (LEFM) principles to fatigue crack growth, is shown to be stress ratio dependent. Constant amplitude fatigue crack growth rates are shown to depend on maximum stress, S_{max}, apart from stress intensity factor range, ΔK and stress ratio, R, above a certain S_{max}/σ_{ys} value. This limit approaches unity for high positive stress ratio (open cracks) and reduces to very low values for negative stress ratios. Crack closure is shown to explain this S_{max} effect. Over the range of stress ratios and maximum stress levels considered, crack closure consolidates da/dN vs. ΔK_{eff} data into a narrow scatter band.

INTRODUCTION

Paris et al (1) showed that fatigue crack growth rates could be uniquely related to stress intensity factor. The rapid burst of fatigue crack growth research, that followed, brought out the limitations of da/dN vs. ΔK correlation into sharper focus. Discovery of crack closure phenomena by Elber (2) led from a da/dN = $f_1(\Delta K, R)$ relation to a da/dN = $f_2(\Delta K_{eff})$ where ΔK_{eff} is the crack closure corrected stress intensity factor range. Application of fracture mechanics parameter ΔK or ΔK_{eff} to fatigue crack growth hinges on the assumption of small scale yielding. This has led to the thumb-rule that $S_{max}/\sigma_{ys} < 0.33$). Constant amplitude fatigue crack growth data are generally generated at low stress levels for long cracks. Systematic study of stress dependent growth rate behavior are usually carried out for small cracks as it is believed that the stress intensity factor cannot describe the small crack tip stress/strain field adequately. Jira et al (3) investigated small and large surface cracks (50 µm to 8 mm) at R = 0.5, 0.1 & -1.0 with a wide range

---

* Fatigue & Fracture Group, National Aeronautical Laboratory, Bangalore 560 017, India

of S_{max}/σ_{ys} values ($0.2 < S_{max}/\sigma_{ys} < 0.9$). They showed that closure measured by an Interferometric displacement gauge consolidated S_{max} effect on growth rate at a given stress ratio.

Systematic study of S_{max} effect on long cracks is sparse. Constant stress intensity factor tests can be thought of as a means to study S_{max} effect on crack growth. Davidson (4) and Hudak and Davidson (5) showed that S_{op}/S_{max} was a function of both R and ΔK, in their constant ΔK tests. Davidson (4) also showed that at lower ΔK ranges the mode-I crack opening level was higher than mode-II crack opening level. This has interesting implication on correlation of experimentally observed crack growth rates with crack closure especially at near threshold ΔK regime. Allison et al (6), in their constant ΔK tests at R = 0.05 on CT specimens of an α/β Titanium alloy, observed crack closure stress intensity, K_{op}, to be a function of crack length even for long cracks. In contrast Brahma et al (7) and Chen and Nisitani (8) obtained a constant K_{op} in their constant ΔK test in single edge notched specimens. Ashbaugh (9) in his crack closure study on CT specimens of different sizes, pointed out that closure values were strongly dependent on crack length, in plane-size and thickness. For a given specimen geometry he observed a loading history effect on closure which can be termed as dK/da effect on crack closure. In these investigations (6,8,9) and in most of the crack closure study reported in ASTM STP 982 (10) experimental crack growth rate data were not reported. It would have been more meaningful to discuss various aspects of crack closure in relation with the crack growth rates obtained under controlled stress intensity tests.

It is seen that crack closure/opening stress under smoothly varying load histories (controlled stress intensity) is not a function of stress ratio alone (10) but depends on stress level, specimen size and other loading/geometric variables. A systematic study of the various aspects involved would help understand fatigue crack growth rate data generated in laboratory specimens and their relevance to the problem of fatigue crack growth in actual structures.

With this in view, the effect of stress level, S_{max}, on fatigue crack growth and crack closure at three different stress ratios are investigated in this paper.

FATIGUE CRACK GROWTH EXPERIMENTS

The material considered is BSS 2L72 Al-Cu alloy sheet material of 2 mm thickness. The chemical composition (weight %) is Cu - 3.8; Mg - 0.55; Si - 0.6; Mn- 0.4 and mechanical properties are E - 73 GPa; σ_{ys} - 330 MPa; σ_{ts} - 480 MPa.

Single Edge Notched Tension (SENT) coupons with an initial notch of 6 mm were used. Automatic crack length measurement and load-displacement data acquisition were made possible with the CMOD gauge. Tests were carried out on a 10 ton Instron servo-hydraulic automated fatigue crack growth test facility at National Aeronautical Laboratory (NAL). The test frequency was 5 Hz. Crack length increments recorded were of the order of 0.125 mm. Anti-buckling guides were used in negative stress ratio tests. Three stress ratios (R = 0.5,-0.5,-1.5) were selected. At each stress ratio three S_{max} values were selected to obtain the S_{max} dependent crack growth behaviour.

The load-CMOD data recorded at various crack lengths were analysed to obtain crack closure stress level as a function of crack length. The point of deviation from linearity in the unloading load-CMOD data was determined based on maximum correlation coefficient of a straight line fit of the data. The stress corresponding to this point was taken as crack closure stress level.

ANALYSIS OF TEST RESULTS AND DISCUSSION

Crack growth rates were plotted as functions of ΔK in Figs. 1, 2 and 3 for R = 0.5, -0.5 and -1.5 respectively. For R = 0.5, in Fig. 1, a unique da/dN vs. ΔK curve was obtained even upto S_{max} = 270 MPa for the Al-Cu sheet material with a yield strength of 330 MPa. It is noteworthy that in spite of the fact that at a stress level of 270 MPa (S_{max}/σ_{ys} = 0.81) the conventional SSY requirement is grossly violated, crack growth rate is describable by the LEFM parameter ΔK. Crack growth rate data for R = -0.5, shown in the Fig. 2, indicates that upto a stress level of 150 MPa the da/dN vs. ΔK data fall in a single scatter band. Growth rates in S_{max} = 200 MPa test does not belong to this scatter band. At any given ΔK growth rates are higher for S_{max} = 200 MPa test compared to that under the too other lower stress levels. The effect of stress level on crack growth rate in R = -1.5 tests is shown in Fig. 3. Tests at 75 MPa, 85 MPa and 100 MPa show distinctly different da/dN vs. ΔK curves. These stress levels are below the SSY requirement and yet a unique da/dN vs. ΔK relation is not observed.

From these limited tests it can be said that the SSY requirements for a da/dN vs. ΔK correlation is not unique but depends on stress ratio. The upper bounds for S_{max}/σ_{ys} below which a da/dN vs. ΔK correlation is obtainable are 270/330, 150/330 and 75/330 , for R = 0.5, -0.5 and -1.5 respectively.

The stress level effect on crack growth rates can be explained through crack closure. The load-CMOD data indicated that the crack was fully open in R = 0.5 tests. The on-line load-CMOD trace on the oscilloscope did not exhibit any knee-point in these test. Crack closure stress ratios, S_{cl}/S_{max}, as a function of crack length are shown in Fig. 4 for all the six test at R = -0.5 and -1.5. It is seen from this figure that crack closure stress ratio is not a unique function of R only. Its dependence on crack length is clearly seen. For both the negative stress ratios considered here, at lower S_{max} levels, the S_{cl}/S_{max} ratio transits from a higher initial stabilized value to a lower stabilized value. Such a trend was observed by Paris and Hermann (11) in a CT specimen at a positive stress ratio. With an increase in the stress level, S_{cl}/S_{max} ratio never stabilizes during the test. At S_{max} = 200 MPa for R = -0.5 and S_{max} = 100 MPa for R = -1.5 cracks close only after application of a large compressive stress. It may be mentioned here that Hudak and Davidson (5) were able to consolidate their crack closure data in the form of a plot of $\Delta K_{eff}/\Delta K$ versus $1/K_{max}$. However we are unable to consolidate our crack closure measurements (Fig. 4) in any suitable format. A more clear understanding of the dependence of crack closure on loading variables and specimen geometry (especially end rotation) is required to unify such data.

The effect of these estimated crack closure levels on crack growth rate are seen in the da/dN vs. ΔK_{eff} plot in Fig. 5. All the nine test data (three stress levels at each of the three stress ratios) fall into a single scatter band. For purposes of comparison , the da/dN vs. ΔK plots are shown in Fig. 6. Needless to say that the CMOD measured crack closure consolidates the stress ratio as well as stress level effects on fatigue crack growth rate.

CONCLUSIONS

1. Small scale yielding ($S_{max}/\sigma_{ys} < ?$) requirement, for application of LEFM principles to fatigue crack growth, is not unique but depends on stress ratio. For an open crack S_{max}/σ_{ys} tends to unity. On the otherhand for large negative stress ratios S_{max}/σ_{ys} can be much less than 0.33 (the value conventionally reported in the literature)
2. The non-ΔK dependent crack growth rate behaviour observed due to the violation of SSY requirement is primarily due to dissimilar crack closure field.

REFERENCES

(1) Paris, P. C., Gomez, M. and Anderson, W. E., Trend in Engineering, Vol. 13, No.1, 1961.

(2) Elber, W., Ph.D. thesis, University of New South Wales U.K. 1968.

(3) Jira, J. R., Weerasooriya, T., Nicholas, T. and Larsen, J. M. ASTM STP 982, 1988, pp. 617-636.

(4) Davidson, D. L., ASTM STP 982, 1988, pp. 44-64.

(5) Hudak, S. J. Jr. and Davidson, D. L., ASTM STP 982, 1988, pp. 121-138.

(6) Allison, J. E., Ku, C. R. and Pompetzki, M. A., ASTM STP 982, 1988, pp. 171-185.

(7) Brahma, K. K., Dash, P. K. and Duttaguru, B., Int. J. of Fatigue, Vol. 11, No. 1, 1989, pp. 37-42.

(8) Chen, Dai-heng and Nisitani, H., ASTM STP 982, 1988, pp. 478-487.

(9) Ashbaugh, N. E., ASTM STP 982, 1988, pp. 186-196.

(10) Newman, J. C. Jr. and Elber, W., ASTM STP 982, 1988.

(11) Paris, P. C. and Hermann, L., "Fatigue Thresholds", Vol.I, Edited by J. Backlund, A. F. Blom and C. J. Beevers, EMAS publication, 1982.

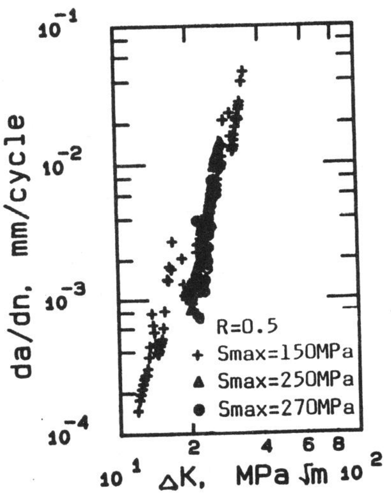

Fig.1: Smax effect on growth rate for an open fatigue crack (R= 0.5).

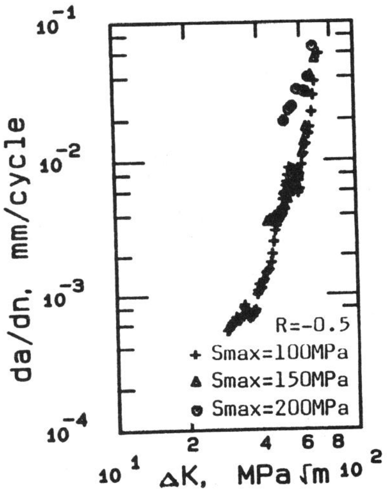

Fig.2: Smax effect on growth rate (R=-0.5).

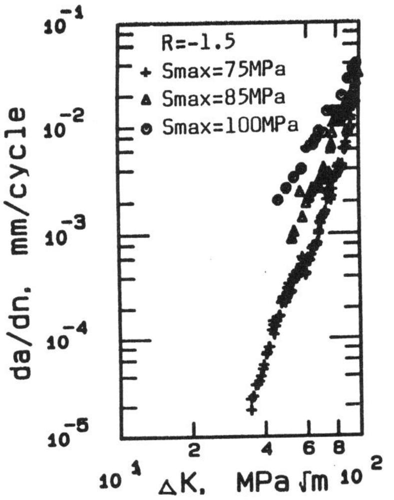

Fig.3: Smax effect on growth rate (R=-1.5).

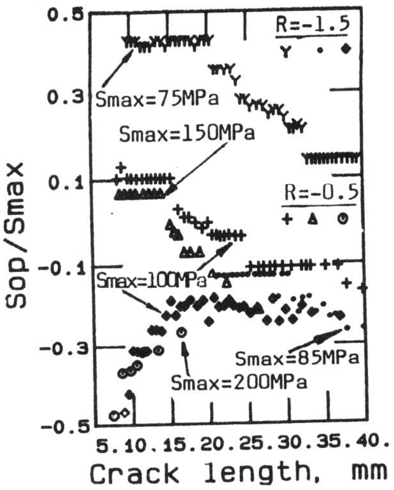

Fig.4: Effect of stress level on S_{op}/S_{max} ratio.

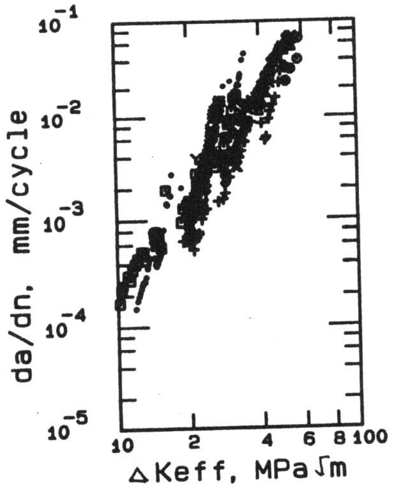

Fig.5: Crack closure consolidates Smax and R effect on growth rate.

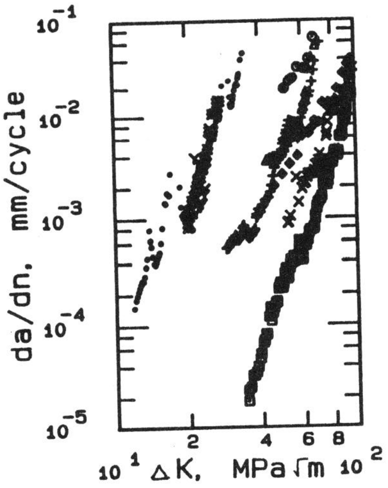

Fig.6: Effect of R and Smax on da/dn vs ΔK relation.