ELASTIC-PLASTIC FATIGUE CRACK GROWTH

J. Polák*, J. Němec and M. Klesnil***

*Institute of Physical Metallurgy, Czechoslovak Academy of Sciences, 616 62 Brno, Czechoslovakia

**Institute of Theoretical and Applied Mechanics, Czechoslovak Academy of Sciences, 120 00 Prague, Czechoslovakia

ABSTRACT

Crack growth rates in low carbon steel were measured under different experimental conditions in elastic and elastic-plastic regions. Through crack data were compared with part through crack results over a wide crack growth rate interval. The fracture mechanics description can be used provided the range of the J-integral corresponding to the unclosed crack is properly evaluated. The short cracks show no threshold and in some cases accelerated crack growth is observed.

KEYWORDS

Fatigue, crack growth, elastic-plastic straining, J-integral range, part through crack, threshold, short crack, crack closure.

INTRODUCTION

To evaluate the fatigue life of the construction or a component subjected to alternating service loading the fracture mechanics concept has been widely used (Paris and Erdogan, 1963, Socie et al., 1979). In this concept the fatigue crack growth rate is related to the stress intensity factor amplitude or to the range of the J-integral. Until now the majority of the data have been collected for long cracks propagating through the whole thickness.

In many cases the actual situation necessitates the evaluation of different crack configurations and part through cracks are of considerable practical interest (Němec, 1982). Moreover, crack growth rate vs. stress intensity factor amplitude plot obtained for long cracks loaded quasielastically cannot be directly applied in the region of high crack growth rates under elastic-plastic straining and for short cracks which exhibit in many cases anomalous behaviour from the point of fracture mechanics approach. In elastic-plastic straining the J-integral was applied (Dowling and Begley, 1976, Dowling, 1976, Polák and Klesnil, 1980). For short cracks the introduction of an "effective crack length" ℓ_o into the expression for stress intensity factor (El Haddad et al., 1979) gave agreement with long crack data though its use has no thorough reasoning and more detailed analysis is necessary (Miller, 1982).

The present work reports the data on long through thickness cracks and part-through cracks in quasielastic and elastic-plastic region and the applicability of fracture mechanics approach is discussed.

EXPERIMENTAL

Specimens were made from low carbon steel (ČSN 42 12010) having 0.15 % carbon. The resulting grain size after vacuum annealing was 40 μm. The active part of the specimen had the shape of a panel with a cross section 6 x 35 mm^2 or of a cylinder with a diameter of 10 mm. In the middle of a rectangular panel holes were bored either through the thickness or to a depth equal to the hole radius. These notches served as crack starters. In the cylindrical specimens a shallow notch having an elastic stress concentration factor equal to 1.04 was machined in the middle of the gauge length. The extensometer touched the specimen surface in the distance of 10 mm across the notch.

The specimens were cyclically strained either in a servohydraulic closed loop testing machine with constant strain rate $\dot{\varepsilon} = 5 \times 10^{-3}\ s^{-1}$ or in a resonance testing machine with constant frequency 50 Hz. Crack growth rates were measured using a travelling microscope. Further experimental details can be found elsewhere (Polák and Klesnil, 1980, Obrtlík and Polák, 1983, Klesnil et al., 1983).

RESULTS

Crack growth rates vs. range of the J-integral obtained on long cracks in central cracked panels are shown in Fig. 1. In the elastic-plastic region, symmetric straining with constant displacement amplitude has been used. ΔJ consists of an elastic and plastic component. The plastic component was evaluated from the hysteresis loop area according to a procedure proposed by Begley and Landes, 1972 (for details see Polák and Klesnil, 1980). ΔJ corresponding to the opened crack has been calculated in elastic-plastic region. In order to keep the ammount of the closure small in elastic region, atleast for higher growth rates, these data are presented in Fig. 1 for stress asymmetry R = 0. Nevertheless, even here closure can be important close to the threshold.

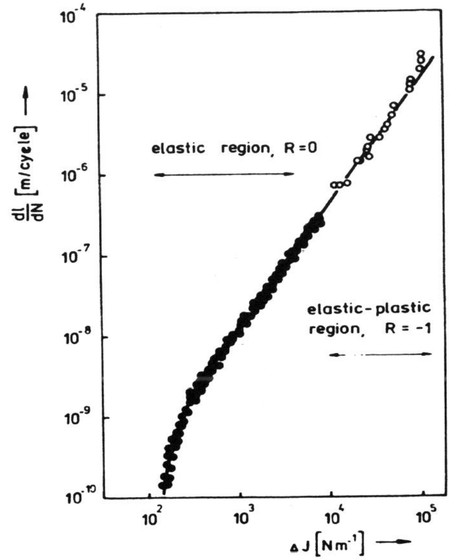

Fig. 1 Long through thickness crack growth rates vs. J-integral range.

It is apparent from Fig. 1 that a single curve can be drawn through the measured points in both the elastic and the elastic-plastic region. For higher crack growth rates the Paris law in the form

$$\frac{d\ell}{dN} = v_o \left(\frac{\Delta J}{\Delta J_o} \right)^{\gamma} \qquad (1)$$

fits the experimental data very well with $\gamma = 1.55$. For crack growth rates smaller than 10^{-9} m/cycle the threshold is pronounced.

In Fig. 2 the long through crack data are represented by a solid line with broken lines showing the scatter band. Simultaneously, experimental points from part through crack data are shown here. In elastic-plastic region the part through cracks were initiated from surface notches. Their shape, as found by heat tinting, was close to that of a semicircle and the crack length was put equal to the radius of the semicircle. Crack lengths were in the interval 0.3 to 5 mm. Two different displacement amplitudes were applied. The J-integral range was evaluated in a similar way to that for long through cracks, i. e. from the hysteresis loop area corresponding to unclosed crack (Obrtlík and Polák, 1983).

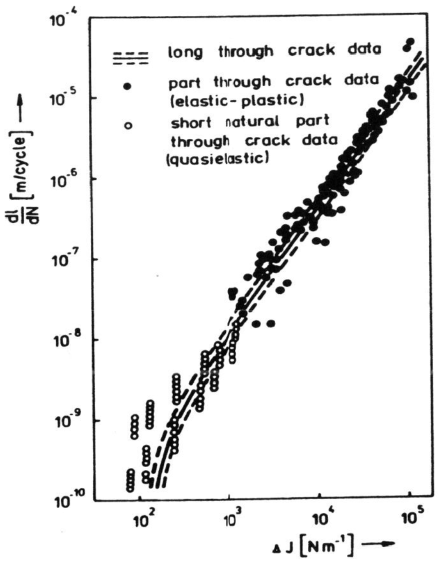

Fig. 2 Part through thickness crack growth rates vs. J-integral range and comparison with long through thickness data.

The scatter of the experimental points is rather high, nevertheless the centre line coincides suprisingly well with long crack data results. Due to the fact, that minimum crack lengths were round 0.3 mm these data extend to crack growth rates down to 10^{-8} m/cycle.

Short cracks having smaller ΔJ and accordingly lower crack growth rates can be produced only without original notches. The natural part through crack data are shown also in Fig. 2. The natural cracks developed a semicircular shape and the crack length was again put equal to the radius of the semicircle. Two stress amplitudes close to the fatigue limit were applied. As for these stress amplitudes the ammount of plasticity is very low, ΔJ was evaluated from K_a values according to the relation $\Delta J = 4\ K_a^2\ /\ E$.

In general, the natural crack growth data are close to the long crack master curve. However, no indication of the threshold is apparent: on the contrary the crack growth rates of small cracks deviate in the direction of higher crack growth rates. Moreover, some dependence on the applied stress amplitude was observed that is beyond the experimental scatter of the data.

DISCUSSION

Present experimental data on crack growth rates under various experimental conditions show that range of the J-integral, ΔJ, is a unifiyng parameter which determines the crack growth rates of fatigue cracks having different shapes and subjected to different stress and strain amplitudes. This conclusion is in agreement with the finding of Dowling and Begley (1976) and Dowling (1976) on A 533B steel, who have used different test specimen geometries. It was also shown that to achieve this unique representation the closure phenomena must be taken properly into account. In the high crack growth rate region the appropriate J-integral range must be evaluated which corresponds to the opened crack. The results on short natural cracks exhibit no fatigue threshold. This is in agreement with the fact that for these small cracks the crack closure does not take place. Provided that the crack length is higher than the average grain diameter the crack growth rates are close to the extrapolation of the master curve according to Paris´ law down to these smallest crack growth rates. However, some anomalously high growth rates, compared with the extrapolation, are observed. This short crack problem requires further attention.

CONCLUSIONS

The following most important conclusions can be drawn from the present work:

(i) Crack growth rates measured on long through cracks plotted vs. J-integral range agree very well with data on part through cracks both in elastic-plastic and quasielastic region except the neighbourhood of the threshold.

(ii) Surface cracks, both these initiated at notches and the natural ones, acquire the crack front close to the semicircular and for crack lengths higher than grain diameter the fracture mechanics description of the crack growth rates can be used. Short cracks exhibit no threshold, even higher crack growth rates compared to the extrapolation are observed.

REFERENCES

Begley, J. A., and J. D. Landes 1972 . The J-integral as fracture criterion. In Fracture Toughness, ASTM STP 514, ASTM, Philadelphia. pp. 1 - 20.

Dowling, N. E., and J. A. Begley (1976). Fatigue crack growth during gross plasticity and the J-integral. In Mechanics of Crack Growth, ASTM STP 590, ASTM, Philadelphia, pp. 82 - 103.

Dowling, N. E. (1976). Geometry effects and the J-integral approach to elastic-plastic fatigue crack growth. In Cracks and Fracture, ASTM STP 601, ASTM, Philadelphia, pp. 19 - 32.

El Haddad, M. H., K. W. Smith, and T. H. Topper (1979). Fatigue crack propagation of short cracks. J. Engng Mater. Technology 101, 42 - 46.

Klesnil, M., J. Polák, and P. Liškutín (1983). Behaviour of short cracks close to the fatigue limit. Kovové Mater. 22, in print.

Miller, K. J. (1982). The short crack problem. Fatigue Engng Mater. Structures 5, 223 - 232.

Němec, J. (1982). Damage to structures by high-cycle fatigue. Fatigue Engng Mater. Structures 5, 205 - 214.

Obrtlík, K., and J. Polák (1983). Fatigue growth of surface cracks in elastic-plastic region. Fatigue Engng Mater. Structures - submitted to.

Paris, P. C., and F. Erdogan (1963). A critical analysis of crack propagation laws. Trans. ASME, J. Basic Engng 85, 528 - 534.

Polák, J., and M. Klesnil (1980). Fatigue crack propagation in elastic--plastic region. Kovové Mater., 18, 578 - 590.

Socie, D. F., J. Morrow, and W. C. Chen (1979). A procedure for estimating the total fatigue life of notched and cracked members. Engng. Fracture Mech., 11, 951 - 959.