A TECHNIQUE FOR MEASURING CRACK LENGTH AND LOAD IN COMPACT FRACTURE MECHANICS SPECIMENS USING STRAIN GAUGES

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ABSTRACT

The calibrated strain on the back face (the face opposite that from which the slot is machined) of compact tension (CT) and T-type wedge opening load (WOL) specimens provides a method for measuring crack length when load is known or for measuring load when crack length is known.

The relationship between crack length, back face strain and load for these specimens is described for any linear elastic material. This method is simple, reliable, sensitive and inexpensive and has for some test situations several advantages over the closely related crack opening displacement (COD) technique. In particular, the back face strain increases linearly with crack length for constant stress intensity (except for very deep cracks in CT specimens). Also, for constant back face strain, the stress intensity decreases more rapidly with increase in crack length for both specimens than for constant COD conditions. The technique has good potential for developing into a more sensitive crack monitor than has previously been achieved and is ideal for incorporation in computerized/automated crack growth testing.

KEYWORDS

Crack length; load; back face strain; stress intensity factor.

INTRODUCTION

The characterisation of cracked test pieces by linear elastic fracture mechanics is based on three requirements - the specimen compliance, applied load and crack length. Knowledge of these parameters is common to fracture toughness testing and studies of sub-critical crack growth such as fatigue and stress corrosion. For the standard specimen types used, compliance is well documented and loads can be accurately assessed from strain-gauged load cells.

Crack length measurement, however, has been identified by Clark and Hudak (1975) as a major source of test variability and Deans and Richards (1979) have assessed the relative merits of the currently available methods of crack length determination.

The present study outlines a method of measuring crack length (or load) directly from strain gauges attached to a specimen and shows how this technique can be applied as an extremely sensitive crack monitor for fracture and fatigue testing and also how it may be applied to automated testing.

TECHNIQUE

Full experimental details of the technique have been published by Deans and Richards (1979) and Richards and Deans (1980). Basically, it was shown from finite element studies that measurement of the compressive back face strain (the face opposite that of the notch) on a CT specimen provides a method of monitoring crack length when the applied load is known or load when crack length is known. The studies showed that the back face strain (BFS) varies linearly with load (P) for varying crack length and it was also shown that the BFS varies linearly with a/W for constant stress intensity (Fig.1).

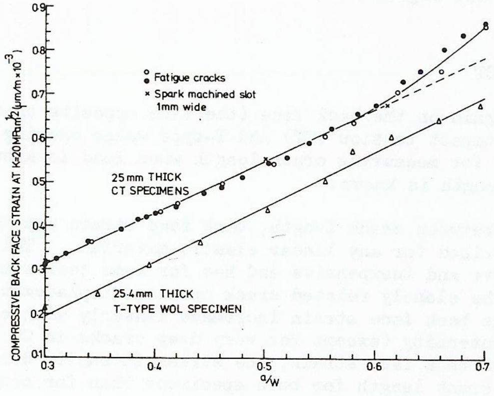

Fig. 1. Variation in compressive back face strain at constant $K = 20\mathrm{MPam}^{\frac{1}{2}}$.

Having developed the BFS technique as a simple and reliable method of measuring crack length for both CT and T-type WOL specimens, the next step is to present the results in a form which is independent of specimen size and Young's modulus of the material. Thus, if A(a/W) is a function of (a/W) and (BFS), the results in Fig. 1 can be given by;

$$(\mathrm{BFS}) = A(a/W)\cdot P$$

Introducing the normalising parameter, $P^* = P/B\cdot W\cdot E$, where B is the specimen thickness, W the width and E is Young's modulus, then

$$(\mathrm{BFS}) = A^*(a/W)\cdot P^*$$

where $A^*(a/W)$ is a function of (a/W). Thus,

$$A^*(a/W) = \frac{(\mathrm{BFS})}{P}\cdot B\cdot W\cdot E.$$

Using this procedure, A^* (a/W) is independent of specimen dimensions and material type for CT and T-type WOL geometries and BFS can be determined for any specimen size and value of E. Values of A^* as a function of a/W for both CT and T-type WOL specimens have been computed by Deans and Richards (1979) and Richards and Deans (1980). The calibration experiments showed that crack length can be measured to ~ 0.25mm whilst much smaller increments of crack growth of 0.02mm can be detected.

APPLICATION OF THE BACK FACE STRAIN TECHNIQUE

Fatigue Crack Initiation and High Crack Resolution Experiments

From the foregoing work, it is important to appreciate that, in the authors' experience, high crack resolution experiments should not be attempted using back face strain gauging without careful attention to the load measuring circuit and the alignment and stability of the specimen loading and gripping train. The crack resolution capability of the BFS technique also depends on the duration of the test and on the crack depth as well as many other factors. In one experiment, a fatigue crack was initiated at $\Delta K = K_{max} = 20\mathrm{MPam}^{\frac{1}{2}}$ in a 25mm thick T-type WOL specimen with a spark machined slot ~ 0.7mm wide. The initial a/W = 0.3 was unfavourable for high resolution but the test duration of a few hours was relatively favourable. Extreme care was taken in monitoring both strain and machine load signal. The change in crack length with number of fatigue cycles is shown in Fig. 2. The crack lengths ascribed are computed from a deep, full penetration calibration. In reality, cracking initiates at or near the specimen mid-thickness and grows as a 'thumb-nail' crack until it meets the specimen surface. Fatigue crack initiation was observed after 5000 cycles as a 'thumb-nail' equivalent to a full-thickness increment of 0.01mm (Fig.2).

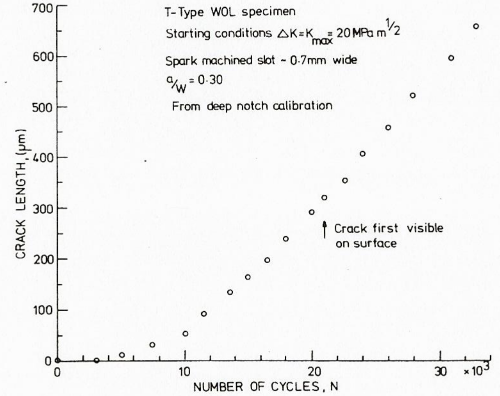

Fig. 2. Initiation and growth of a fatigue crack from a spark machined notch as measured by BFS technique - a/W = 0.3

Only after 21000 cycles was the crack visible on the specimen surface, equivalent to a full-thickness crack of ~ 0.32mm, as measured by BFS. The same test was monitored using a 40A dc 'potential drop' method and crack initiation was detected after ~ 15000 cycles when the full-thickness crack was 0.07mm. While this was superior to visual assessment, the BFS method was almost an order of magnitude more sensitive.

In a second test a similar specimen with a spark machined slot ~0.25mm wide and of a/W = 0.7 was used which was favourable to crack resolution but of unfavourable test duration. The test was started at $\Delta K = K_{max} = 12.9 MPam^{\frac{1}{2}}$. Crack initiation was again detected (Fig. 3) when cracks equivalent to ~ 0.01mm, from a deep crack calibration, were observed. Visual observations were first made after 800000 cycles when the crack was ~1.4mm long, as indicated from BFS measurement. Thus, the degree of 'bowing' of the crack is considerably greater in this test where the conditions are near to the fatigue initiation limit.

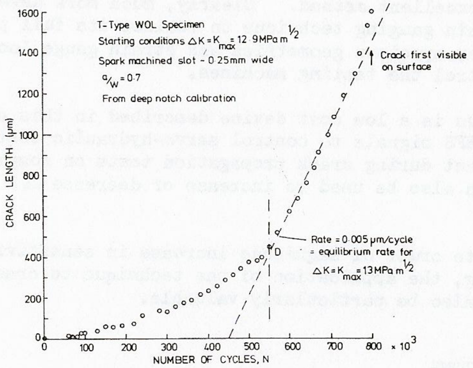

Fig. 3. Initiation and growth of a fatigue crack from a spark machined notch as measured by BFS tequnique - a/W = 0.7

Again, the 40A dc potential drop technique was shown to be much less sensitive than the BFS method. In Fig. 3 the equilibrium rate of crack growth for a deep fatigue crack remote from the slot is drawn for comparison. It is interesting to note that the crack does not behave as a 'deep crack' until the point 'D', (Fig. 3), is reached when the equivalent of ~ 0.5mm growth has occurred.

Fatigue crack initiation is usually defined as the limit of crack detection by whatever means of measurement is being used and is not normally better than 200μm. The use of the BFS technique would improve the definition of crack initiation to ~ 20μm or better and may help provide a new 'dimension' to crack initiation or re-initiation studies in the future.

Threshold Fatigue Crack Growth Studies

It has been shown by Deans and Richards (1979) and Richards and Deans (1980) that for constant BFS there is a decrease in stress intensity with increasing crack length (Fig. 4) and that the rate of decrease was faster than the comparative rate of decrease in COD. This characteristic would therefore be especially useful in obtaining threshold stress intensity values for fatigue crack growth, ΔK_o. Under constant BFS control, the ΔK and fatigue crack growth rate decreases in a smooth, continuous manner and at a pre-determined rate dependent on specimen geometry and initial a/W.

This would be a major advantage over the current method of establishing ΔK_o where specimen loads are reduced by arbitrary amounts and cycling until either crack growth continues or no growth can be detected in up to ~ 10^7 cycles.

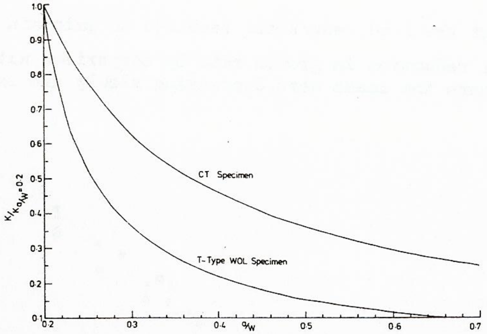

Fig. 4. Decrease in stress intensity with increasing crack length for constant back face strain.

Fatigue tests were performed on the same 3.5% NiCrMoV steel as used previously (Deans and Richards, 1979) using both CT and T-type WOL specimens. In each case a fatigue crack was initiated in a closed loop hydraulic fatigue machine under load control and grown at a low value of ΔK, whilst monitoring the amplified mean and alternating voltage from the back face strain gauges. The test was then stopped and switched to control from the back face strain gauges, thus maintaining these same values of mean and alternating voltage (constant BFS). The results obtained (Fig. 5) show that the fatigue crack growth rate does indeed decrease with increasing crack length in the T-type WOL specimen.

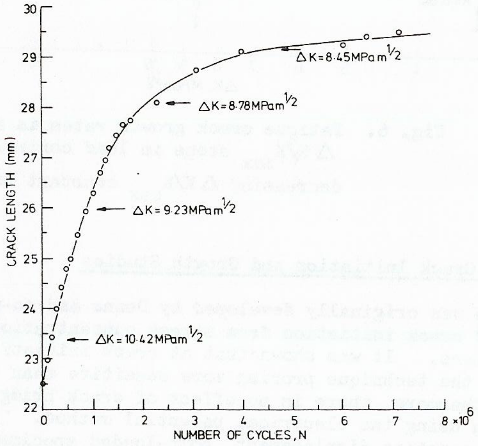

Fig. 5. Change in crack length with number of cycles in a T-type WOL specimen under constant back face strain conditions.

Determination of fatigue crack growth rates at two different values of R, $(\sigma_{min}/\sigma_{max})$, (Fig. 6), shows good agreement with tests where the load was reduced every 0.5mm of crack extension to maintain 'constant' ΔK and K_{max} conditions (Lindley and Richards, 1979). At the higher values of R there is some indication that the load reductions required to maintain 'constant' $\Delta K/K_{max}$ caused some overall reduction in growth rate by comparison with that from the BFS controlled tests where the loads were decreasing slowly and smoothly.

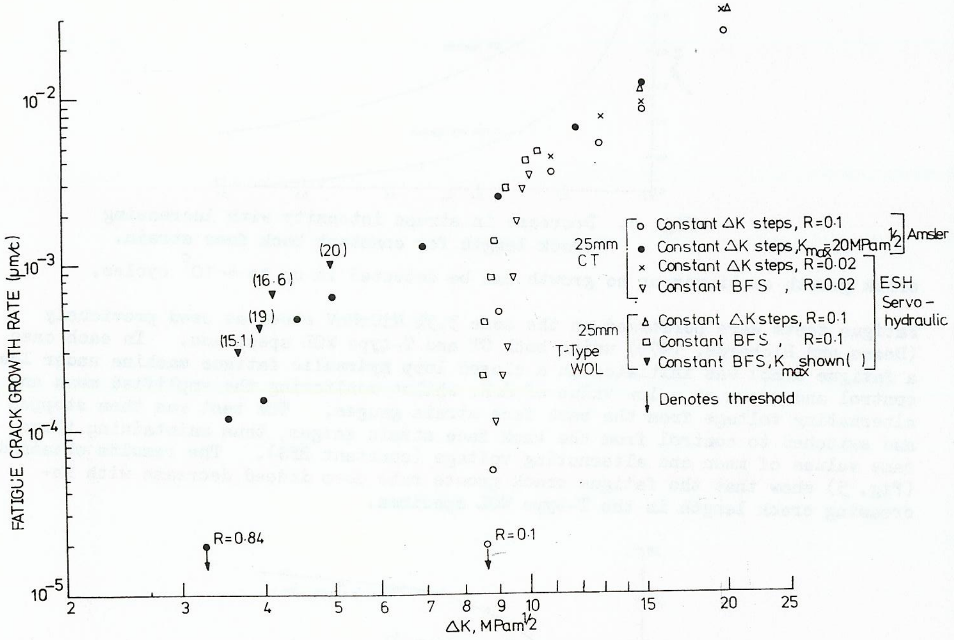

Fig. 6. Fatigue crack growth rates in air using $\Delta K/K_{max}$ steps in load control or decreasing $\Delta K/K_{max}$ constant BFS conditions.

Stress Corrosion Crack Initiation and Growth Studies

The BFS technique was originally developed by Deans and co-workers (1977) to study hydrogen assisted crack initiation from stress concentrations using notched, self-loaded WOL specimens. It was shown that at crack initiation, a sudden increase in BFS occurred, the technique proving more sensitive than the dc potential drop technique. Furthermore, there is no effect of crack bridging which underestimates crack length when using the electrical potential method. Specimen load was also monitored on the constant displacement, bolt-loaded specimens and results showed no load relaxation over 10000h testing at room temperature. Clearly, this vindicated the use of such specimens for the test application and highlighted the benefit of the technique for multi-point testing.

The BFS technique has also been successfully applied to crack growth monitoring in hydrogen gas (Akhurst, 1979) at a variety of temperatures and pressures. Crack length resolution of 25μm was reported in these studies.

FUTURE DEVELOPMENTS

Inevitably, it will not be long before most testing will be controlled and monitored by computer. The same computer will also process the test data and present it in a suitable form. A major advantage of such development would be the reduction in test supervision and 24-hour-a-day testing. Furthermore, increasingly complex tests could be performed which more closely simulate many in-service conditions. For such testing to be meaningful, it is necessary to have a reliable and sensitive measure of crack length. The technique described in this paper provides an excellent method. Clearly, much more development work needs to be done on the strain gauging technique to realise its full potential e.g. the examination of other specimen geometries and strain gauge locations and the use of BFS signals to control the testing machines.

Especially ingenious is a low cost device described in this conference (Briggs and Smith) which uses BFS signals to control servo-hydraulic test machines such that ΔK remains constant during crack propagation tests on compact geometry specimens. The same device can also be used to increase or decrease ΔK at a pre-determined rate.

With the approximate order of magnitude increase in sensitivity over other methods of crack monitoring, the application of the technique to crack initiation and re-initiation should also be particularly valuable.

CONCLUSIONS

The technique described has been shown to be a reliable and sensitive crack monitor for many aspects of cracked specimen testing. Crack resolution is approximately an order of magnitude better than that obtainable with the established methods.

Back face strain gauging provides an excellent method for incorporation into computerised testing. Since the output from the strain gauges can be readily converted for input to standard data logging systems, the overall monitoring of multi-point testing programmes becomes less labour intensive. With the added advantage of high stability over long test times, data acquisition should become less onerous and the significant cost benefits make the BFS technique an extremely attractive proposition.

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