Surface fatigue crack growth in vessels and welds. Measurement methods and analysis of large cracks

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Abstract

Fatigue crack propagation results obtained in four-point bending at base metal, heat affected zone and weldment of butt welds made of pressure vessel steel BS 4360-50D (C-Mn steel) are reported. Low cycle fatigue tests were performed in air at RT at a range of stress ratio R between 0.1 and 0.7. The shape of surface cracks was continuously recorded using potential drop methods. At very low stress ratios crack closure was observed.

The results were presented in the form of propagation curves da/dN vs. Δ K. Threshold values were also recorded; they decreased with increasing R values.

The crack growth rate results for the CT specimens of weld and parent metal fall into a narrow band with the weldment results being the fastest at high $K_{rms}$ values and parent plate data the slowest. HAZ results generally lie between the weld and the base metal data.
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1 Introduction

The available data on material behaviour used in the manufacture of pressure vessels, pipes, nozzles and other components provide a reliable basis for design. However, with the growing number of newly developed steels and other materials the volume of mechanical and qualitative tests is increasing rapidly.

As the quantitative investigations on full size structures are very expensive, computations and experimental tests are usually performed on simplified models; in fatigue studies these are frequently notched plates or bars specially developed for fracture mechanics tests. For the fatigue tests performed on BS4360-50D steel, surface crack plates in bending (SCB) were considered a suitable choice. These results were compared with a second set of tests conducted on compact type (CT) specimens.

The specimens which are used for generation of fatigue crack growth data generally have through-thickness cracks which propagate uniformly across the thickness. However, in structures fatigue cracks initiate at the surface and grow in different orientations. These cracks may eventually become through-thickness cracks depending on the complexity of the stress distribution across the section. In many cases the crack front is not uniform and stress intensity factor variations along the crack front may be large. It is not clear whether the large crack front curvature and differences in fatigue resistance due to orientation can affect the crack growth behaviour of a part-through crack geometry. Because of the limited data available on the geometries and other factors influencing fatigue crack growth, a detailed comparison of the surface and through thickness crack propagation would be helpful.

The prediction of crack propagation rates, crack shape formation and crack path are important in design when establishing the safe life. Apart from Stress Intensity Factor (SIF) values, a knowledge of the maximum load variations is also needed, although for cracked structures, a much lower and very conservative load is sometimes used. This is particularly so in nuclear, high
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pressure or high temperature installations.

Tests and Analysis

The study of surface crack propagation was conducted in 4-point bending at constant amplitude and at room temperature, and the results compared with compact type tests. Two different solutions are required for CT and SCB geometries. Those used for CT specimens are described in the literature, p.ex. ASTM and, being frequently used, are well known.[1]

On the other hand, the crack-front curvature and shape variations under fatigue loading of SCB specimen is adequate evidence that the stress intensity factor varies around the periphery of a surface crack. A small curvature of crack front in through-crack geometries has also been observed, but the assumption that $K$ remains constant is only valid as long as the differences between the mid section and surface lengths are small compared to the average crack length. The crack growth rates around the periphery of a part-through crack are generally bounded by the rates at the maximum depth and the surface intersection points. Thus $K$ solutions for these locations are required to study the fatigue behaviour of such crack geometries.

Many of the $K$ solutions are derived based on models of infinite or semi-infinite plates containing the particular crack geometry. Hence the infinite-model solution is modified so as to account for the various geometric constraints being removed due to the finite size of the component. Irwin (1962) was the first to derive an exact stress intensity factor solution for an embedded elliptical-crack in an infinite plate under tension.

The general form of $K$ solutions is given by

$$K = \frac{\sigma \sqrt{\pi a}}{E(k)} F(a / c, a / B, c / W, \theta)$$

where $B$ and $W$ are specimen thickness and width respectively. The function $F$ is called a correction factor which accounts for the geometric effects due to the
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The finite size of the specimens or components. The applied stress could be due to either tension or bending. The expressions for $F$ are different under tension and bending. For the present study fatigue tests were performed under pure bending, hence only bending solutions are considered. The two most critical locations around the crack boundary are the maximum depth and the surface-intersection points, the solutions for these two locations are $K_a$ and $K_c$ respectively. The KOTERA et al [2] expressions for part-through cracks in bending with the HOLDBROOKS [3] finite width correction factor $B_f$ were found suitable. The solutions are:

$$K_a = M_1 M_2 B_f \frac{\sigma_B \sqrt{\pi a}}{E(K)}$$

$$K_c = M_{12} B_f \frac{\sigma_B \sqrt{\pi a}}{E(K)}$$

where $M_1$, $M_2$ and $M_{12}$ and $E(K)$ are geometry functions and $\sigma_B$ is bending stress.

The CT specimens were only tested at a stress ratio $R = 0.7$ while SCB specimens were tested at stress ratios of 0.08, 0.35 and 0.7. All specimens were 25 mm or 34 mm thick, precracked at $R$ equal to 0.1 and after the initiation the cracks were allowed to grow up to 3 mm such, that the plastic zone effects of the notch geometry could be avoided.

The CT specimens were tested using a Mayes fatigue machine at a frequency of 15 Hz. The crack length was measured on one side of the specimen by means of travelling microscope (X50). The crack length on the other side was periodically monitored so as to ensure uniform growth across the thickness.

The SCB specimens were tested in a four point bend-rig using a Dartec closed loop servohydraulic machine and tests were carried out at CA frequency of 3 Hz. Crack length at the surface of the specimen was measured using a travelling
microscope. Crack depth was monitored by the application of the AC crack microgauge unit. The raw data were in the form of crack-geometry dimensions of $2c$ and $a$, and the number of cycles, $N$, elapsed between each measuring period. The average growth rate in either the depth or the surface width direction was determined by secant method.

To calculate SIF at any given location along the semi-elliptical crack boundary, accurate knowledge of the dimensions of the specimen and crack geometry is essential, in particular the maximum crack depth, $a$, which is the most important parameter that influences the accuracy of $K$ solutions. The stress intensity factor $K$ at the maximum depth $K_A$, is much more sensitive to the fluctuations in the depth-measurements than $K_C$, at the surface intersection points. Thus any error in crack depth estimation will result in an incorrect $K_A$ value.

As will be shown from $da/dN$ results, the variations of voltage measurement at the top surface of the SCB specimens by means of crack microgauge unit introduce a large degree of scatter in the growth rate data, in the thickness direction. Although care has been taken to produce accurate calibration curves based on optical microscopic measurement of the crack depth for each specimen, nevertheless the scatter cannot be fully omitted as the fluctuation is consistently present at every occasion that depth measurement has been carried out. However, it is essential to discern the correct trend of the variations in $K$ distribution at particular locations of the crack boundary during the fatigue life of the specimens. This is a formidable task and may be facilitated by the calculation of $K_A$ and $K_C$ using bench marking data. Such results are shown in figure 1 which is plot of $K/\sigma_B$ versus half crack length, $c$. The reason for the choice of $K/\sigma_B$ rather than $K$ is to reduce the fluctuations caused by the applied stress. It is apparent that as the crack grows, $K_C$ increases while $K_A$ reduces. The most important characteristic of these results is the rate of change in $K$. That is, though $K_C$ rapidly increases, $K_A$ very slowly changes with respect to $c$ and the change in magnitude of $K_a$ is very small. This implies, that for a test at fixed applied cyclic stress and load ratio, the range of growth rate data at the maximum depth will be small compared to that at $c$. It would be unsafe to increase the maximum stress as it would result in a large plastic zone at the crack tips at the top surface of the specimen or the whole top surface could
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undergo general yielding.

Under the present study two different notch geometries were used. The specimens tested at R equal to 0.08 and 0.7 had the same initial notch geometry of aspect ratio, a/c of 0.4 (this size notch was semi-elliptical in shape and was made by the spark erosion technique), while the specimen tested at R equal to 0.35 had an initial aspect ratio of 0.2. Although the trend in the K distribution during the fatigue life of the specimens was the same, nevertheless the specimen with the circular arc notch (a/c=0.2) showed a slightly larger SIF value. The reason for this increase is the small effect of width of the specimen which was 115mm compared with that of the other specimens at 120mm.

Results

Figure 2 shows that for a given a, c, and B the values of K decrease as the width W increases. This behaviour can be explained by considering identical flaws in geometrically similar specimens, one specimen being larger than the other. The stress intensity factor at the crack tip of the larger specimen would be smaller, thus the observed behaviour is consistent.

In contrast to the width, the effect of thickness B on K distribution is more severe, as is shown in figure 3 which is a plot of K/σB versus B, for a given a, c, and W. As thickness increases, both Kₐ and Kₑ increase, but the magnitude of Kₐ is more sensitive to thickness changes than Kₑ is. This behaviour can be explained by considering the rectangular cross section geometry of the specimens under pure bending. From simple engineering theory of bending, as the thickness of such a geometry increases, the stress at a fixed distance below the top surface of the specimen increases. Therefore, Kₐ should increase with growing thickness. It should also be noted that at the crack plane the stress variation is not linear across the ligament as is observed at locations far away from that plane. However, the complex stress distribution across the ligament, though non-linear, varies in much the same way as is experienced at other cross sectional locations, i.e. the stress must change across the thickness from tensile stress at the top surface of the specimen to a compressive one at the bottom. Naturally, a neutral surface exists which is positioned beyond the maximum
crack depth and it is curved - its curvature depends on crack geometry and its position with respect to the cross section.

The slight increase in $K_c$ can be due to the reduction of stress gradient resulting in an increase of stress concentration around the surface flaw. The increase in $K_a$ and $K_c$ depends on the size and aspect ratio of the semi elliptical crack. In the two cases studied doubling the thickness results in the incremental increase in $K_a$ and $K_c$ having a 25:1 ratio for the circular arc geometry of aspect ratio of 0.2 while for the spark-erosion notch geometry of $a/c$ equal to 0.4 the same ratio is 10:1. The ratio of $K_c$ to $K_a$ is approximately 0.5 and 0.9 for the two aspect ratios of 0.2 and 0.4 respectively.

**Comparison of growth rate results of CT and SCB specimens**

The growth rate data obtained at a stress ratio of 0.7 for both geometries have been compared and are shown in figure 4. It will be noted that growth rate data of SCB specimens are slower than the CT specimen results.

The mean air data line is also drawn in this figure. From examination of the results of other workers it was found that their CT or SEN specimen crack propagation data at a stress ratio of 0.7 usually lay above their mean air data line while their $dc/dN$ data of SCB specimens tested under the same load ratio lay below their mean air data line. The same behaviour is demonstrated by the results of the present study. The influence of crack closure at this stress ratio is not present. The mechanism of crack growth is generally the same in both types of specimens. Therefore, the fatigue crack growth mechanism could not have resulted in the discrepancy observed in the data. The state of stress at the surface of the SCB specimen is that of plane stress while the CT specimen crack front experiences plane strain conditions, except at the free surfaces. It has been reported in the literature that crack growth rate under plane strain conditions is faster than under plane stress. Because the crack growth advancement in a CT specimen occurs mainly under the plane strain state while the crack tip at the surface intersection points of the SCB specimen is under plane stress condition, it is reasonable to expect that the $dc/dN$ data of SCB should be slower than the $da/dN$ data of the CT specimen.[4].
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The influence of plastic zone shape ahead of the crack tip on the delayed retardation of crack growth in CT and CCT (Centre Crack Tension) specimens of alloys of steel and aluminium has been reported by TANAKA et al [5]. However the differences in growth rate of the two geometries were negligible. The plastic zone shape of CT specimen was smaller than that of CCT specimen as reported by Larsson and Carlsson in 1973, and delayed retardation of the CT specimen was also smaller than that of the CCT specimen. The influence of plastic zone shape on the overall crack propagation rate under constant amplitude loading does not seem to be significant in either of the specimens but when the behaviour at the surface is compared to the general state of stress ahead of the crack front the effect of plastic zone cannot be negligible.[6]

The behaviour of surface crack specimens at the free surface is comparable to that of CCT specimens and the plane stress plastic zone shape would be similar in both SCB and CCT specimens. Therefore the plastic zone area would be larger at the free surface of a SCB specimen compared to that of a CT specimen. The increase in plastic zone area influences the stress distribution ahead of the crack tip which can reduce the growth rate due to residual plastic deformation being present. Thus the growth rate at the surface of the SCB specimen would be smaller than the overall growth rate of the CT specimen.

It should be noted that the plastic zone size ahead of the crack tip for CT and CCT specimens are nearly the same but the extension of the plastic zone at angle of approximately 70° is twice bigger in CCT specimens than that of compact specimens.

Weldments

The butt-welded CT specimens of 25mm thickness were tested under random load at a frequency range of 0.15 Hz and Q factor (mean load/rms of load) of 8. Two different spectra were used for the loading, broad band and triple-peaked spectrum. The load system for the CT specimens was supported on a 100 KN Mayes fatigue machine. [7]
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The SCB specimens of weld and HAZ were tested under pure bending by means of the Dartec fatigue machine. The frequency-bandwidth and Q factor were the same as for the CT specimens. For both weld and HAZ test-pieces, one half of specimens was tested under a flat broad band signal and the other under a BP spectrum load.

The crack growth rate results for the welded CT specimens are shown in Fig. 5, which is a plot of \( \frac{da}{dN} \) vs. \( K_{\text{rms}} \) (MN/m\(^{3/2}\)). The spectrum shape of the signal was a broad type BB with a bandwidth 0-15 Hz. The crack growth data at the surface intersection points in the weld and HAZ of the SCB specimens is much faster and the results are included in the same figure.

The results obtained for SCB specimens under CA loading are presented in Fig. 6. They fall into a comparatively narrow scatterband with the fastest results in weldment and the slowest in the base metal.

Conclusions

1) In the initiation period the quasi-elliptical shape of the surface crack subjected to the bending fatigue is influenced by the starter notch form. However, later in the fatigue life, it is the overall form of the specimen which will govern the crack shape.

2) Surface crack growth under constant amplitude loading was analysed. The results show that the variation of stress intensity factor at the maximum depth of the surface crack plate under pure bending hardly changes in contrast to that at the surface intersection points during the fatigue crack propagation life of such specimens. Due to such a small change the \( \frac{da}{dN} \) results cover a very small range when compared to \( \frac{dc}{dN} \) data.

3) \( K_a \) and \( K_c \) values of a surface crack are strongly influenced by the changes of the geometry of the specimen.

4) Under random loading the crack growth rate in the weldment was slower
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than in the parent metal of 50D steel at low $K_{r_{ms}}$ and faster at large $K_{r_{ms}}$ values when CT specimens were used for testing. However, the trend was similar to that observed under CA loading. A comparison of the results under the two types of loading showed that the fatigue resistance of weldment was lower under random loading.

References


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Fig. 1. Stress intensity factor vs half crack length for range of R-values

Fig. 2. Variation of stress intensity factor with width

Fig. 3. Variation of stress intensity factor with thickness

Fig. 4. Comparison of surface crack growth (at the surface intersection points) and through-thickness crack growth of 50D steel in air
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Fig. 5. Comparison of the crack growth results of HAZ, weld and 50D steel

Fig. 6. Comparison of the results obtained for HAZ, weldment and parent metal using SNP geometry in air