THE EFFECTS OF MECHANICAL AND ENVIRONMENTAL VARIABLES ON FATIGUE CRACK PROPAGATION IN BUTT-WELDED JOINTS

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ABSTRACT

Fatigue crack growth at low stress intensities has been studied in class 6 weld material in a salt water environment with particular emphasis being placed on the influence of stress ratio and frequency. Frequency levels of 30 Hz and 0.25 Hz were employed in 3.5% sodium chloride solution at R-values of 0.08 and 0.7.

Comparing the present results with previously obtained data in air [1] show that in general fatigue crack growth rates were lower and the threshold stress intensity range, ΔK_{th}, higher in the salt water environment than in laboratory air. This decrease in growth rates was limited to certain ranges of stress intensity range, ΔK, depending on the stress ratio, and was independent of frequency. Decreasing the frequency of loading from 30 Hz to 0.25 Hz had no effect on growth rates, as a significant increase in growth rates was observed in the data obtained in air. Fatigue crack growth behaviour in stress-relieved welds in both air and salt water was the same as above except that there was a marked reduction in stress intensity range. Crack closure and environmental effects are proposed to explain the decrease in growth rates.

KEYWORDS

Fatigue; crack growth; weldment; corrosion fatigue; stress ratio; frequency; threshold.

INTRODUCTION

It is known that the useful life of cyclically-loaded welded structures containing crack-like defects is controlled by the crack growth rate and is determined by the growth of the defect to a critical size. A knowledge of fatigue crack growth rates in weld metal under different mechanical and environmental conditions is important in the fail-safe design of welded structures.

Recent experiments from the North Sea show that corrosion fatigue in off-shore structures is a major cause of failures as off-shore structures are subjected to continuous load cycling due to the action of wind and waves in a corrosive environment. Most experimental studies to obtain the effect of mechanical and environmental variables on fatigue crack propagation rates and threshold stress intensity factors have been conducted on base metals [2 - 4]; only a few studies have been concerned with welded joints [1, 5 - 7].

In previous work [1] fatigue crack propagation in parent plate and butt-welded joints of BS 4360-50D steel was investigated and it was shown that the fatigue properties of butt-welded joints without any post-weld heat treatment was superior to those of base metal. This was due to the compressive residual stresses around the crack tip. The present work was undertaken to investigate the influence of stress ratio, frequency and sea-water on fatigue crack growth of weldments and to provide suitable data for assessing the integrity of butt-welded components in off-shore structures.

Materials And Experimental Details

The base material was BS 4360-50D steel used in the fabrication of offshore structures. Chemical composition and mechanical properties are in [8].

The blanks for the specimens were prepared by the butt-welding of two plates, each about 50 mm wide, 95 mm long and of thickness 25 mm. All the welds were ground flat. The joint preparation was a double 'Vee' and incorporated a 2 mm root gap. Manual arc-welding and the wide weave technique were employed for manufacturing the specimens using a C/Mn welding rod. The chemical composition and mechanical properties of the weld metal are given in Table 1.

Standard compact type specimens 79.5 mm wide were used in the present investigation and notches were orientated parallel to the welding direction and in the weld metal. Some of the welded specimens were stress relieved at 650°C for half an hour. The fluid was collected via channels made from a thin aluminium plate and fixed around the specimen. A perspex strip was fastened to the channel on the side where optical viewing was made, see Figure 1. The salt water was introduced into the notch of the specimen via a thin plastic tube and the flow rate was controlled by gravity feeding.

Tests were carried out on a Mayes servo-hydraulic fatigue machine, of 100 kN capacity. Near-threshold and regime II fatigue tests were performed in 3.5% NaCl solution at stress ratios, R, of 0.08 and 0.7 and loading frequency of 30 Hz. To investigate the effect of frequency in regime II in a salt-water environment, tests were performed at R-values equal to 0.08 and 0.7, while the cyclic frequency was reduced to 0.25 Hz.

The tests on stress-relieved specimens were performed at stress ratios of 0.7 and loading frequency of 30 Hz both in air and salt water environments.

A travelling microscope was used to measure the crack length, a, and the stress intensity factor, K, was calculated using the standard formula recommended for compact type geometry.

RESULTS

The effect of stress ratio, R, on fatigue crack growth rate of the weldment in salt-water is shown in Figs. 1 and 2 at loading frequencies of 30 Hz and 0.25 Hz respectively. At near-threshold stress intensity the crack growth rates and ΔK_{th} values are strongly dependent on R. This effect diminishes with increasing stress intensity range, ΔK, Fig. 1.

Reducing the loading frequency from 30 Hz to 0.25 Hz resulted in a slight effect of frequency at high growth rates of the order of 10^{-4} mm/cycle, this is shown in Fig. 3 for stress ratios of 0.08 and 0.7.

The composite plots of da/dN versus ΔK in air [1] and this investigation are presented in Figs. 4 and 5. These results indicate that in general crack growth rates in salt solution are lower than the corresponding air data and in particular there is an increase in ΔK_{th} values from 13.75 MPa $m^{\frac{1}{2}}$ in air at 0.08 to 22 MPa $m^{\frac{1}{2}}$, and from 6.7 MPa $m^{\frac{1}{2}}$ at 0.7 to 9.5 MPa $m^{\frac{1}{2}}$ in a salt-water environment at 30 Hz. It is interesting to note that the growth rate curves for air and salt-water intersect at the same values of ΔK at a particular stress ratio irrespective of cyclic frequencies (i.e. 30 Hz and 0.25 Hz). These ΔK values are approximately 32 MPa $m^{\frac{1}{2}}$ at R = 0.08 and 20 MPa $m^{\frac{1}{2}}$ at R = 0.07.

Figure 6 shows the result of tests on stress relieved weldments in air and salt-water at R = 0.7 and cyclic frequency of 30 Hz. Like the results obtained from as-received welds, it shows crack growth retardation in salt solution. Stress relieving appears to reduce the stress intensity factor range ΔK at a fixed growth rate, if the results are compared with the as-received weld presented in Fig. 4.

DISCUSSION

The results obtained at loading frequencies of 30 Hz and 0.25 Hz and two R-ratios (i.e. 0.08 and 0.7) showed a considerable decrease in crack growth rates (see Figs. 4 and 5), compared to air data [1]. This effect could be explained in terms of the solution chemistry and the mechanical interaction between fluid and crack tip geometry [9]. It is possible that due to the nature of the channels used to collect the fluid, the slow flow rate resulted in rapid mixing at the crack tip and in the bulk solution. This mixing process could result in a pH difference between the successive solution at the crack tip and/or the possibility of the used fluid and corroded products being deposited at the crack tip and causing blunting which in turn reduces the growth rates. At lower values of ΔK the growth rate is low and blunting could occur as a result of general corrosion. However, at higher values of ΔK the growth rates are faster and it is possible that in this range the environmental action complements the mechanical stresses to enhance growth rates.

Tu and Seth [10] explained the retardation of fatigue cracks in corrosive environments at low ΔK values in terms of deposited corrosion products at the crack tip which will form a protective film and effectively reduce the amount of further corrosion agent entering the crack tip, thus causing a slower crack growth rate at low values of ΔK and thresholds. At high values of ΔK where the growth rate is higher, the corrosion products do not have enough time to pile up, and corrosive agents can enter the fresh fracture surfaces created during the loading cycle to cause further embrittlement without delay.

Radon and co-workers [11] suggested a dissolution process which leads to crack blunting, this mechanism being responsible for the low crack growth rate in sodium chloride solution compared with air at low test frequencies. The dissolution process contributes mainly by increasing the radius curvature at the crack tip, which at high growth rates means that a longer time will be required, since a larger volume of material will have to be moved. Thus high growth rates do not favour crack tip blunting. This explanation agrees well with the present results, as there is less retardation at high growth rates.

Previous work by Rhodes and Radon [12] suggested two distinct processes by which crack propagation may occur. One is due to chemical action at the crack tip enhanced by the presence of a tensile stress, referred to as 'stress-assisted dissolution'. The other is due to local mechanical failure, enhanced by the presence of an adverse environment, 'environment assisted fracture'. These two processes are mutually competitive. Stress assisted dissolution, by the action of microbranching and blunting, actually inhibits mechanical fracture. Conversely, if mechanical failure proceeds sufficiently rapidly, there is no time for dissolution to take place before the crack-tip passes any particular point in the material. Thus the two processes are not simply superimposed. Either one or the other will dominate crack propagation.

In the present investigation it appears that stress-assisted dissolution has dominated the process of crack growth. However, no fractographic examination was made, thus the mechanics of microbranching cannot be confirmed in this study. Crack closure phenomena due to Elber [13] have often been used to explain the observed effect of stress ratio on fatigue crack growth rates. According to this concept, the crack closure stress intensity factor K_{Cl} at low stress ratios is above the minimum stress intensity factor and thus the effective stress intensity factor range responsible for crack growth is substantially reduced. At high stress ratios, the crack remains open for the whole or larger part of the load cycle and thus the crack closure effect becomes less pronounced; in other words, the contribution of fatigue crack extension may take place only during those portions of the cycle where the crack remains open. This argument seems to explain the effect of R ratios for the present results. In Figs. 1 and 2 a decrease of growth rate with decreasing R-ratio was observed for a given value of ΔK.

The data summarised in Fig. 3 shows that frequency effects occur only at high growth rates. At near-threshold and intermediate ΔK values, the growth rates appear to be the same. This observation conforms with those of other investigators [14, 15]. The results suggest two distinct regions [15] which are identified as frequency-independent and frequency-dependent regions I and II respectively. In region I where the growth rate is only ΔK dependent, the exposure of clean metal surfaces at the crack tip is a rate controlling step. In region II where the crack growth rate is only frequency dependent, it is likely that some reaction-step in hydrogen-metal interaction at the crack-tip controls the growth rate.

CONCLUSIONS

As a result of a study of the effect of environment on fatigue crack growth in butt-welded joints, the following conclusions may be drawn.

1. Fatigue crack growth ratios are, in general lower, and threshold ΔK_{th} values are higher in salt water solution than in air.

2. In a salt water environment where crack growth continues at a reduced rate, a critical value of ΔK exists irrespective of loading frequency beyond which rapid growth ensues. This ΔK value is approximately 32 $MPa\ m^{\frac{1}{2}}$ at R = 0.08 and 20 $MPa\ m^{\frac{1}{2}}$ at R = 0.7, which are the intersections of air and salt water environment curves.

3. Stress ratio, R, was found to influence the fatigue crack growth rate in salt solution, increased R values being accompanied by increased growth rates.

4. A frequency effect is not significant in a salt water environment for the welds used in this study.

5. Stress relieving does not change the shape of the curves in air and salt water; it only reduces the stress intensity range ΔK.

REFERENCES

1. Moghadam, S.P., Balthazar, J.C., and Radon, J.C, (1984). Fatigue crack propagation in the parent material and the weldment of a structural steel. To be published in Fracture Prevention in Energy and Transport Systems, Rio de Janeiro.

2. Musuva, J.K., and J.C. Radon (1981). Threshold of fatigue crack growth in a low-alloy steel. Advances in Fracture Mechanics, 5th Int. Conf. on Fract., Cannes. pp. 1365-1372.

3. Radon, J.C. (1979). Influence of environment on threshold in fatigue crack growth. Metal Science, 13, pp. 411-419.

4. Paris, P.C., Bucci, R.J., Wessel, E.T., Clark, W.G. and Mager, T.R. (1972). Extensive study of low fatigue crack growth rates in A533 and A508 steels. ASTM STP 513, pp. 141-176.

5. Maddox, S. (1970). Fatigue crack propagation in weld metal and heat affected zone material. Metal Const. & B. Weld. J., 2, pp. 285-289.

6. Sandifier, J.P. and Bowie, G.E. (1978). Fatigue crack propagation in A 537M steel. ASTM STP 648, pp. 185-196.

7. Poon, C.J. and Hoeppmer, D.W. (1979). The effect of frequency and environment on fatigue crack growth behaviour of ASTM A533 Grade B Class 1 weldment material. Int. J. Fatigue, pp. 141-152.

8. Zheng, C.Q., and Radon, J.C. (1982). Basic Tensile Properties of a low-alloy steel BS 4360-50D. Fracture Mechanics Technology Applied to Material Evaluation and Structure Design, Melbourne, Australia, pp. 243-256.

9. Hartt, W.H., Tennant, J.S. and Hopper, W.C. (1978). Solution chemistry modification with corrosion fatigue cracks. ASTM STP 642, pp. 5-18.

10. Tu, L.K.L., and Seth, B.B. (1978). Threshold corrosion fatigue in steels. J. of Testing & Eval., 6, pp. 66-74.

11. Radon, J.C., Branco, C.M. and Culver, L.E. (1976). Crack blunting in corrosion fatigue of mild steel. Int. J. Fract. Mech., 12, pp. 467-469.

12. Rhodes, D., and Radon, J.C. (1979). Environmental effects on crack propagation in aluminium alloys. Fatigue of Eng. Mater. and Struct., 1, pp. 383-393.

13. Elber, W., (1971). The significance of fatigue crack closure. ASTM STP 486, pp. 230-242.

14. Musuva, J.K. and Radon, J.C. (1979). The effect of stress ratio and frequency on fatigue crack growth. Fatigue of Eng. Mater. & Struct. 1, pp. 457-470.

15. Vosikovsky, O. (1975). Fatigue crack growth in an X-65 line pipe steel at low cyclic frequencies. J. Eng. Mater. & Tech., 97, pp. 298-304.

TABLE 1.

Welding Electrode BS 639 : E 4311 R21 (3)

Chemical Composition (Weight)

Element	C	Mn	Si	S	P
%	0.06	0.58	0.43	0.02 max	0.03 max

Mechanical Properties

Yield Strength N/mm^2	448
UTS N/mm^2	510
% Elongation	22
% Reduction of area	50
Charpy V-notch at RT (20°C) 80 joules	

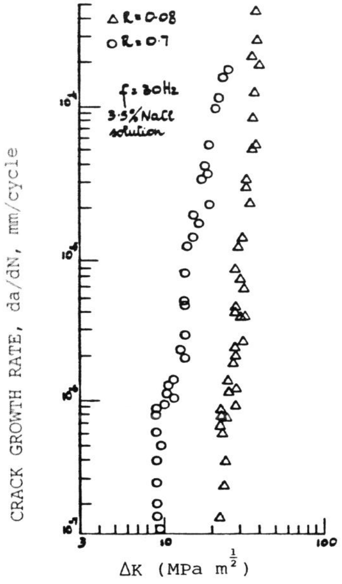

Fig. 1. Effect of stress ratio on weldment in salt solution

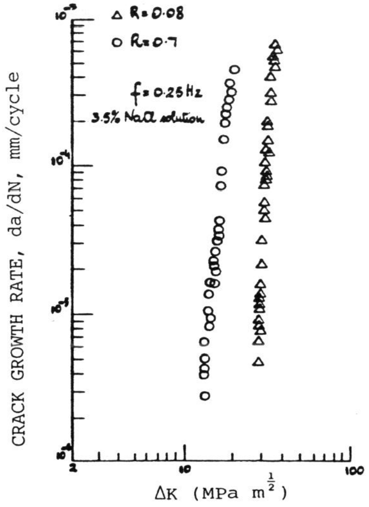

Fig. 2. Stress ratio effect on weldment using CT specimen in salt solution at 0.25 Hz

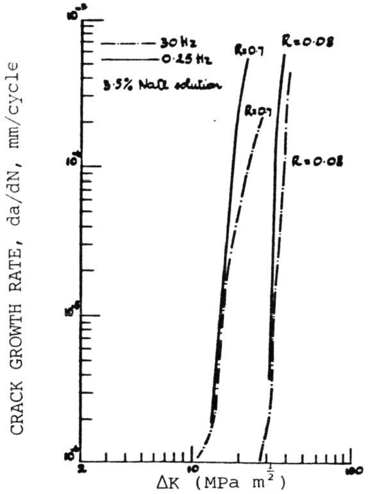

Fig. 3. Frequency and stress ratio effects on weldment in salt solution

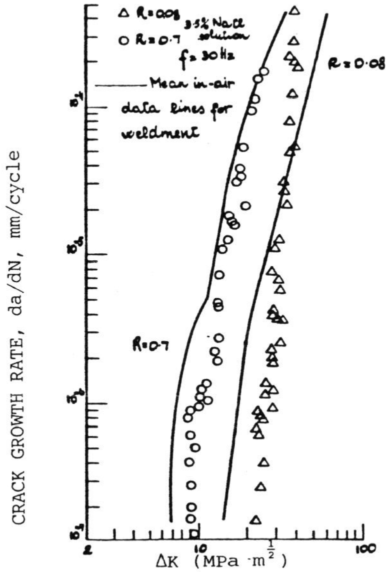

Fig. 4. Stress ratio effect on weldment in air and salt solution

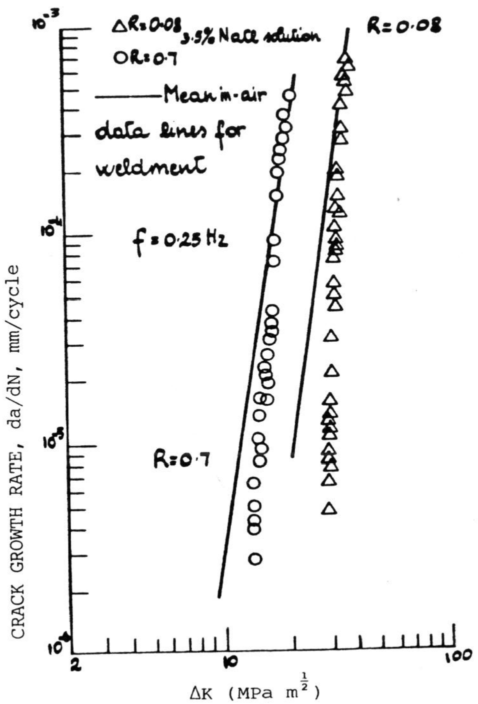

Fig. 5. Effect of Stress ratio on weldment in air and salt solution

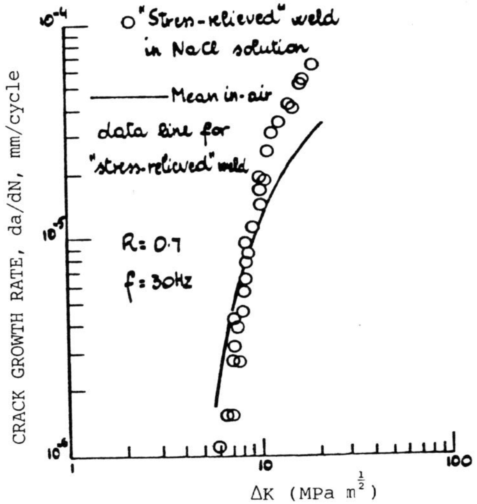

Fig. 6. Stress relieved weldment in air and salt solution