EXPERIMENTAL STUDY OF SURFACE CRACK PROPAGATION IN AN E 36 STEEL

M. Truchon, H.-P. Lieurade

Institut de Recherches de la Sidérurgie Française (IRSID)
185, Rue du Président Roosevelt 78105 Saint Germain-en-Laye (France)

ABSTRACT

The propagation of surface cracks under fatigue loading was observed on 20 mm thick plates made of E 36 steel (AFNOR standard). The experiments were carried out in tension or four-point bending.

Crack growth monitoring was made by using a crack front marking technique. Fatigue crack growth data and crack shape evolution were analysed with the help of solutions found in the literature.

KEYWORDS

Surface cracks ; Part-through crack ; crack front marking ; fatigue crack growth.

INTRODUCTION

Surface crack propagation is an important problem which deals with the development of defects just after their initiation. In many cases it can be shown that a major part of the propagation time elapses while the crack is a part-through crack.

Analysis of fatigue crack growth from a surface flaw of any configuration is usually performed by assuming the flaw as a semi-circular or a semi-elliptical crack for the sake of simplicity. Since the first attempt of Irwin (1962), several numerical analyses have been performed by Shah and Kobayashi (1971), Marrs and Smith (1971), Grandt and Sinclair (1971), Newman (1977), Chang (1977), Maddox (1975), Raju and Newman (1979) to calculate the Irwin stress intensity factors of semi-elliptical cracks. So, it is possible to analyse surface crack growth by using a fracture mechanics approach.

As the fatigue crack growth properties are generally measured with specimens containing through-thickness cracks, it was found important to verify if the same phenomenological laws can be applied to the case of crack growth in specimens containing partial thickness cracks.

EXPERIMENTAL CONDITIONS

Material

The experimental work was carried out on a structural steel (AFNOR E36-Z steel) which is generally used in the construction of offshore platforms. This material was hot-rolled into plates of 20 mm thickness. Its chemical composition and mechanical properties are given in Tables 1 and 2.

TABLE 1. Chemical Composition of the E36-Z Steel (weight %).

C	Mn	Si	S	P	Ni	Cr	Mo	Al	N_2
0,145	1,40	0,292	0,003	0,006	0,42	0,075	0,031	0,019	0,012

TABLE 2. Mechnical Properties.

σ_y (N/mm^2)	σ_{UTS} (N/mm^2)	Elongation to rupture (%)	Reduction in Area (%)
370	530	33.5	75

Specimens

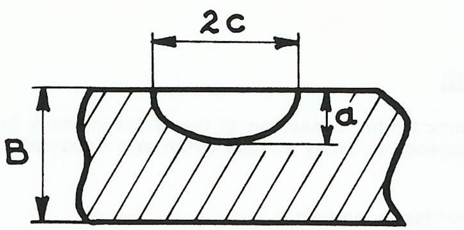


Fig. 1. Definition of crack shape parameters.

Preliminary tests were carried out on CT specimens (B = 20 mm ; W = 80 mm) with L-T orientation and KF specimens (B = 5 mm ; W = 20 mm) with L-S orientation, in order to measure the fatigue crack growth rate (FCGR) of this material in the two directions of interest. As shown on the sketch of Fig. 1 which defines the crack shape parameters, the development of $\frac{da}{dN}$ will be compared to the L-S results and that of $\frac{dc}{dN}$ to the L-T's.

Part-through crack (PTC) experiments were carried out on plates of 500 mm long, 100 mm wide and 20 mm thick. A surface notch of 2 mm deep was machined on one face, at the center of the specimen. Three types of notches were used, which only differ by the width : 5, 25 and 50 mm.

Test Conditions

The tests were carried out in tension or in four-point bending, with a sine cycle, at the frequency of 10 to 30 Hz depending on the amplitude of the applied load. The influence of the load ratio was also studied and this parameter varied from $\sim$0.1 to 0.5.

Fatigue Crack Growth Monitoring

As it is impossible to measure directly the depth of the crack a, crack growth monitoring was achieved by using a marking technique.

The method for producing beachmarks on the fracture surface, consisted in reducing the load amplitude by half (Fig. 2) while the maximum load was kept constant. It was found that the beachmark was visible only if there was a small propagation during the reduced-load program. In order to check this point, we used an A.C. potential-drop method to visualize the cracking process :

- the potential was made to vary by a certain quantity to produce a beachmark,
- then it was made to vary ten times this quantity between each beachmark.

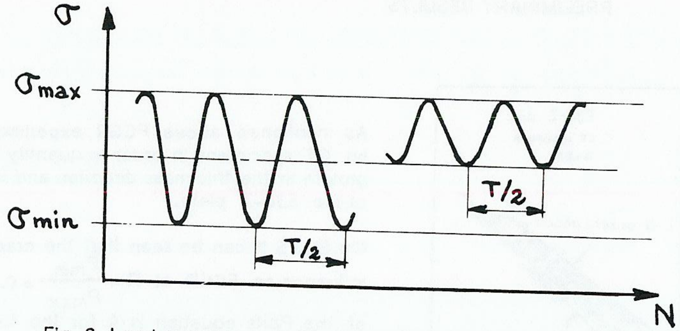


Fig. 2. Load sequence used to generate crack front markings

Figure 3 shows two examples of the fracture surfaces obtained by this technique and corresponding to different shapes of initial defects.

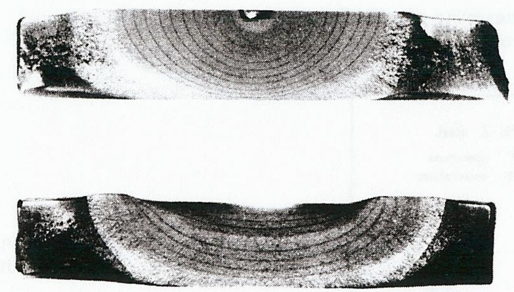


Fig. 3. Some examples of crack markings

The sketch of Fig. 4 shows how the experimental data were used to derive the FCGR between two beachmarks.

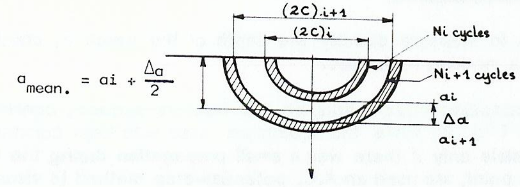


Fig. 4. Derivation of fatigue crack growth rates.

PRELIMINARY RESULTS

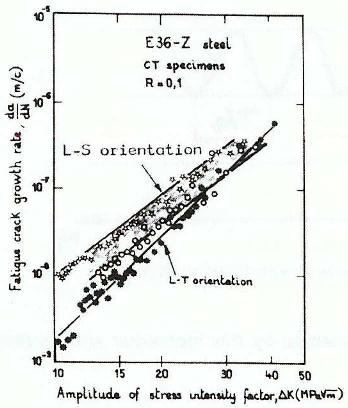
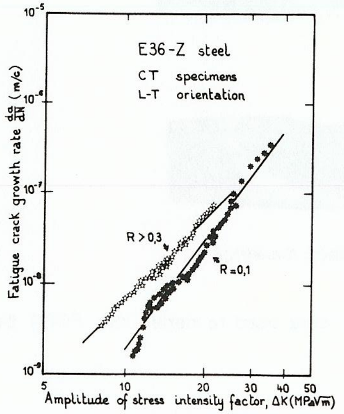


Fig. 5. Effect of sampling on FCGR of the E-36-Z steel.

As mentioned above, FCGR experiments were carried out on CT specimens in order to quantify separately the crack growth in the thickness direction and in the width direction of the E36-Z plate.

On Fig. 5 it can be seen that the crack orientation has an influence on FCGR at $R = \frac{P_{min}}{P_{max}} = 0.1$. The exponent m of the Paris equation is 4 for the L-T orientation and 3 for the L-S orientation.



The influence of R ratio on FCGR was studied only in the case of the L-T orientation.

The results are presented in Fig. 6 and show that the slope m becomes equal to 3 when $R \geq 0.3$.

Fig. 6. Effect of mean stress on FCGR of the E36-Z steel.

PART-THROUGH CRACK (PTC) GROWTH

Crack Front Development

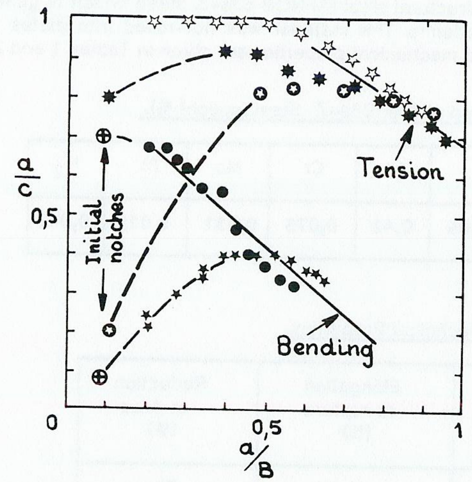


Fig. 7. Crack shape development as a function of loading mode.

In this work, the shape of crack-tip contour line was examined by the observation of beach-marks on the fracture surface which had been generated by the above-mentioned procedure.

The configuration of a PTC in a plate is determined by the three following factors : depth of crack a, length 2c and plate thickness B, as shown in Fig. 1. In the present analysis, the relation between two factors was examined : the depth-to-length ratio $\frac{a}{c}$ and the depth-to-thickness ration $\frac{a}{B}$.

The dependency of $\frac{a}{c}$ on $\frac{a}{B}$ is show in Fig. 7 for the two loading modes : tension and bending. These results are in good agreement with the observations made by other authors (Iida and Kawahara, 1975 ; Burck, 1977) that is :

- whatever the initial notch shape, the PTC always tends toward an equilibrium shape ;
- in a first stage, the crack shape depends mainly on the notch shape ;
- in the equilibrium stage, it depends mainly on the loading mode. In the case of tension, the ratio $\frac{a}{c}$ remains approximately constant as the crack grows ; in the case of bending this ratio decreases.

Analysis of Fatigue Crack Growth Rate (FCGR)

Derivation of stress intensity factors. Solutions for the evaluation of the stress intensity factor of semi-elliptical surface cracks have been proposed by many authors (Shah and Kobayashi, 1971 ; Raju and Newman, 1979).

Generally, the stess intensity factor can be written in the form :

$$K = M \times \sigma \sqrt{\frac{\pi a}{Q}} \qquad \text{with } Q = \phi^2 - 0.212 \left(\frac{\sigma_{max}}{\sigma_y}\right)^2$$

ϕ = complete elliptical integral of the second kind and M, a correction factor which depends on the position along the crack front and on the loading mode. This factor takes into account the effects of the crack shape, free surface and finite thickness. We used the solution of Raju and Newman (1979) in the case of tension and the solution of Shah and Kobayashi (1971) in the case of bending. For the two solutions, it was possible to calculate the stress intensity factor in the width direction and in the thickness direction.

PTC growth in tension. Results obtained for this mode of loading are summarized in Fig. 8 and Fig. 9, and compared to the basic FCGR data obtained on CT specimens. As shown on these diagrams, PTC growth in tension is correctly described by Paris type equations. The constants C and m of these equations depend on the crack growth direction : for the particular cases of surface FCGR and in-depth FCGR, the constants are the same as those generated with the help of CT specimens, in the L-T and L-S orientations respectively.

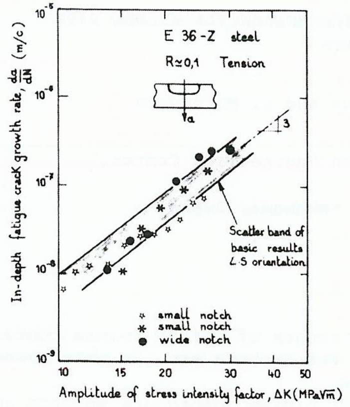


Fig. 8. In-depth FCGR for tension loads.

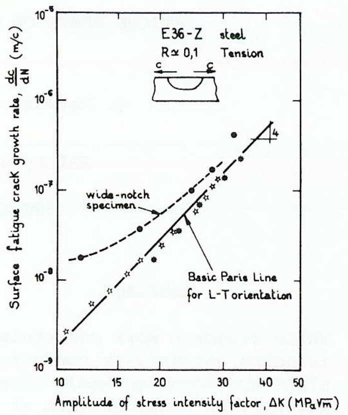


Fig. 9. Surface FCGR for tension loads.

Some parameters have an influence on these results : for example, it can be seen on Fig. 9 that surface FCGR is increased when the starter notch is wide. This can be easily explained by the facts that the crack nucleates in the middle of the wide notch and that the first ($\frac{dc}{dN}$; Δk) points are obtained when the crack width is still smaller than the notch width. So, the differences in FCGR observed at the given Δk value are mainly due to a stress concentration effect.

PTC growth in bending. Results obtained for this mode of loading are summarized in Fig. 10 and compared to the basic FCGR data obtained on CT specimens. In contrast with the tension mode of loading, the FCGR observed in bending do not conform very well with the CT specimens results : they fall within the same scatterband but it is not possible to fit the same Paris lines as previously mentioned with these PTC growth data.

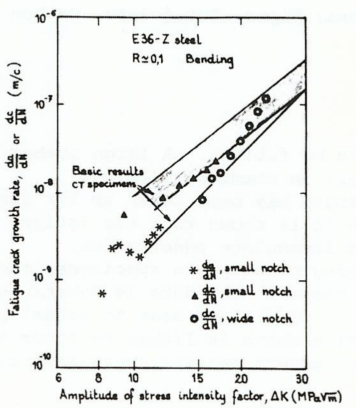


Fig. 10. FCGR of part-through cracks for bending loads.

Further work is needed to elucidate this behaviour, as it is important to notice that so poor a correlation with basic FCGR results also means that the prediction of PTC growth in bending will be poor.

Finally, let us notice that in the case of the wide-notched specimen, the in-depth FCGR remained constant all along the test (not shown in Fig. 10).

CONCLUSION

Part-through crack (PTC) growth experiments were carried out on 20 mm thick plates of a structural steel (AFNOR E36-Z steel).

A method for generating beachmarks on the fracture surface was developed to monitor crack growth.

It was shown that the crack shape depends on the loading mode and that its evolution is correctly described by typical laws relating the ratio a/c of in-depth crack length to surface crack length, to the crack depth a.

FCGR analysis showed that PTC growth was correctly described in the case of tension, by a fracture mechanics approach based on the same Paris' equations as in the unidimensionnal configuration.

Poor correlations were observed in the case of bending.

REFERENCES

Burck, L.K. (1977). Eng. Fract. Rech., vol. 9, p. 389-395.

Chang, J.B. (1977). ASTM STP 687, p. 156-167.

Grandt Jr, A.F. and G.M. Sinclair (1971). ASTM STP 513, p. 37-58.

Iida, K. and M. Kawahara. IIW Doc. XIII-790-75, University of Tokyo, NAUT Report n° 9011.

Irwin, G.R. (1962). Trans. ASME, J. Appl. Mech., p. 651.

Marrs, G.R. and C.W. Smith (1971). ASTM STP 513, p. 22-36.

Newman Jr, J.C. (1977). ASTM STP 687, p. 16-46.

Raju, I.S. and J.C. Newman (1979). Eng. Fract. Rech., vol. 11, p. 817-829.

Shah, R.C. and A.S. Kobayashi (1971). ASTM STP 513, p. 3-21.