BOTH SHORT AND LONG FATIGUE CRACK GROWTH IN AN AUSTENITIC STAINLESS STEEL AT 650°C

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Continuous fatigue tests in a 316L(N) stainless steel at 650°C are conducted on notched and pre-cracked CT specimens. Fatigue crack growth analysis of both type of specimens reveals two different behaviours. Cracks emanating from notched specimens exhibit a characteristic short crack behaviour whereas propagation of long cracks from pre-cracked specimens are significantly influenced by the stress ratio R. Differences between short and long fatigue cracks are analysed using the crack closure concept. An experimental measurement of the closure level K_{op} using an elastic compliance method can explain both behaviours. A relationship between measured crack opening stress ratio U and stress ratio R is also proposed.

INTRODUCTION

Short crack studies initiated by Pearson (1) have revealed the inadequacy of linear elastic fracture mechanics (LEFM) to take into account the growth of short cracks. This behaviour is characterised by higher crack growth rates for small cracks compared to long cracks for an equivalent applied stress intensity factor range ΔK (K_{max}-K_{min}). The crack closure concept developed by Elber (2) has been initially introduced to explain the effects of stress ratio R upon fatigue crack growth. The use of the effective stress intensity factor range ΔK_{eff} rather than ΔK has been widely generalised. Jono (3), Liaw (4) and Verreman (5) have shown that in the case of cracks emanating from notches, plasticity-induced closure plays a major role and differences in the crack growth behaviour of long and short cracks result mostly from different closure behaviours.

Following short fatigue crack growth tests carried out at the CEN-SACLAY (AMORFIS program) by Laiarinandrasana (6) on 316L(N) notched CT specimens, long crack growth behaviour on standard pre-cracked CT specimens is investigated. Experimental results of crack closure measurements are presented and investigations based on Elber's crack closure model are conducted in order to rationalise both behaviours and to take into account the variation of stress ratio R.

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MATERIAL AND EXPERIMENTAL PROCEDURE

The material used in this study is an austenitic stainless steel (316L(N)) provided as a 30mm thick rolled plate, annealed at 1100°C and water quenched. All crack growth tests were performed using standard compact tension specimens (CT) with a width W=50mm, a thickness B=25mm and a crack length ratio a/W≥0.55. Short crack growth studies were conducted using machined notched specimens with a notch tip radius of about 100μm . Long cracks were obtained using standard pre-cracked specimens. A Walter & Bai servo-mechanical testing machine equipped with a 100kN load-cell was used for the tests. The operating cycling frequency was about 0.07Hz. All tests were carried out at 650°C under load controlled conditions. Load point displacements δ(t) were measured using an extensometer attached to the specimen. Crack lengths a(t) as a function of time were determined using a DC-potential drop method. The crack growth Δa as a function of the number of cycles N was obtained using a calibration curve between Δa and DC potential. The tested pre-cracked specimens with their respective loading conditions are listed in table 2.

Table 2 : Fatigue test conditions of pre-cracked CT specimens

Specimen number	Load ratio R	Load ΔF (kN)	a/W	T (°C)
CT74	0,1	6	0.55	650
CT75	0,1	7	0.55	600
CT76	0,1	9.6	0.55	600
CT77	0,1	11	0.55	600
CT78	0,1	9	0.55	650
CT84	-1	6	0.55	650
CT85	-5	6	0.55	650
CT88	-3	6	0.55	650

Crack opening levels were determined using the unloading elastic compliance method programmed on a micro-computer to acquire load and clip-gage data at a frequency of 20hz. An offset method was used to accurately identify the crack opening load level P_{op} as shown in Figure 1. P_{op} is defined as the knee point (deviation from linearity) on a P-Δδ subtracted curve which represents the deviation from the best fitted (by linear regression) loading elastic line. The accuracy of the crack opening load P_{op} obtained using that technique is less than 5% of the total load range ΔP. The tests were conducted at a stress ratio of R=0,1 apart from CT84, CT85 and CT88 which were conducted at R=-1, -3, and -5, respectively.

RESULTS AND DISCUSSIONS

Crack growth behaviours

Figure 2 shows the relation between crack growth rates da/dN and ΔK for notched specimens. This example reveals the peculiar anomalous behaviour of short cracks initiated at notched zones as it has been commonly reported (Jono (4), Ogura (8) and Verreman (5), Polvora (7)). After an initial high value, crack growth rate decreases continuously until it reaches a minimal value. At this stage, either crack arrest is obtained or the crack growth rate increases again with a correlation similar to those obtained for long crack growth baseline data. The fatigue crack growth rate of very short cracks, less than 50μm, can be characterised by the following Paris law:

$$\frac{da}{dN} = 9{,}7\,10^{-8}\,\Delta K^{2{,}98} \qquad [1]$$

with da/dN in mm/cycles and ΔK in MPa$\sqrt{m}$.

For long cracks growing in pre-cracked CT specimens, the da/dN versus ΔK curve does not exhibit such discrepancies as it can be seen in figure 3. The Paris law curve issued from these tests is given by:

$$\frac{da}{dN} = 2{,}71.10^{-7}\,\Delta K^{2{,}46} \qquad [2]$$

This curve is in good agreement with a recent European data compilation on 316L(N) steel at 650°C (9). A comparison made in figure 4 shows that, for the same nominal value of ΔK, the crack growth rate of short crack is globally twice than obtained for long crack .

Crack closure measurements

According to Elber's crack closure concept, the suitable parameter to describe fatigue crack growth rate is the effective stress intensity factor range ΔK_{eff} that represents the part of the applied load cycle for which the crack tip is open. ΔK_{eff} is defined as :

$$\Delta K_{eff} = K_{max} - K_{op} = U\,\Delta K \qquad [3]$$

where K_{op} and U are the crack opening level and the stress opening ratio, respectively. Using the definition of stress ratio $R=K_{min}/K_{max}$, K_{op} and U can be obtained from relation [3] as :

$$K_{op} = K_{max}\left[1 - U(1-R)\right] \quad \text{and} \quad U = \frac{1 - K_{op}/K_{max}}{1-R}$$

Since U is assumed to be an unique function of the stress ratio R, these relationships imply that at constant R, K_{op}/K_{max} is constant and K_{op} is only a function of K_{max}.

These assumptions are validated for a wide range of stress ratio R ($-5<R<0{,}1$) in Figures 5 and 6. K_{op}/K_{max} and U are constant during crack growth. Figure 7 shows the relationship between the crack opening stress ratio U and the stress ratio R. Experimental results can be represented by the following best fit expression :

$$\begin{cases} U = 0{,}2R^2 + 0{,}5R + 0{,}7 & -1 \le R \le 0{,}1 \\ U = 0{,}0143R + 0{,}4261 & R < -1 \end{cases}$$

This expression is compared with the one proposed by Drubay (10) which conservatively predicts higher values of U. Since plasticity-induced crack closure occurs mainly in the wake of the crack tip, crack closure for shallow cracks is insignificant ($\Delta K_{eff}=\Delta K$) and equation [1] represents a material intrinsic curve. The significantly different crack growth rate behaviour obtained for different stress ratios when plotted as a function of ΔK (Figure 4) are greatly reduced when plotted as a function of ΔK_{eff}. This is shown in Figure 8 where all curves become independent of R and merge closer to the short crack intrinsic curve.

CONCLUSIONS

Fatigue crack growth tests at 650°C stainless steel were performed using standard CT25 316L(N) specimens in order to examine the effects of crack tip geometry and stress ratio R upon fatigue crack growth rate. The tests revealed that cracks emanating from notched specimens exhibit a characteristic short crack behaviour whereas the propagation of long cracks is significantly influenced by the stress ratio R.

Differences between short and long fatigue cracks are analysed using the crack closure concept. The closure level K_{op} is determined using an experimental elastic compliance method. The results show that long crack growth rates are well correlated with short cracks rate when using the effective stress intensity factor range. Furthermore, it is shown that the crack closure level is a function of the stress ratio R and K_{max}. A relationship between the closure stress ratio U and stress ratio R is proposed for R values included between -5 and 0,1.

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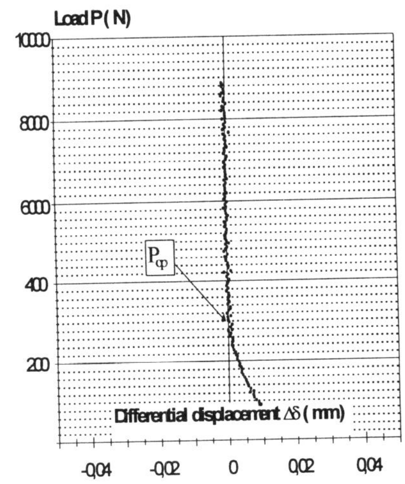

Figure 1: Determination of crack opening level using the offset method.

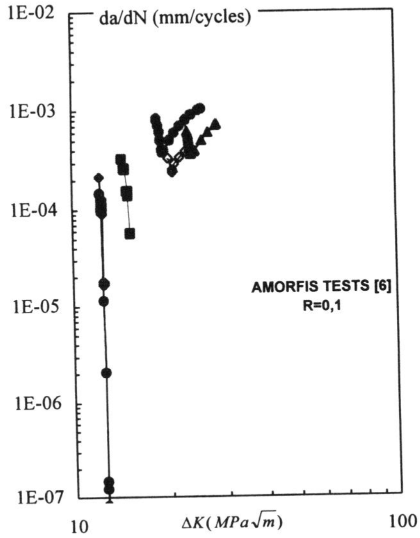

Figure 2:Fatigue crack growth rate versus ΔK for short cracks (laiarinandrasana (6)).

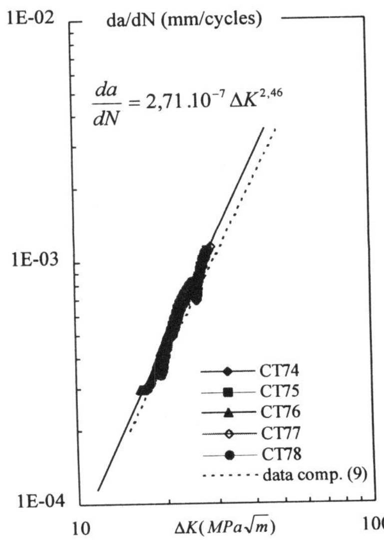

Figure 3: Fatigue crack growth rate versus ΔK for long cracks .

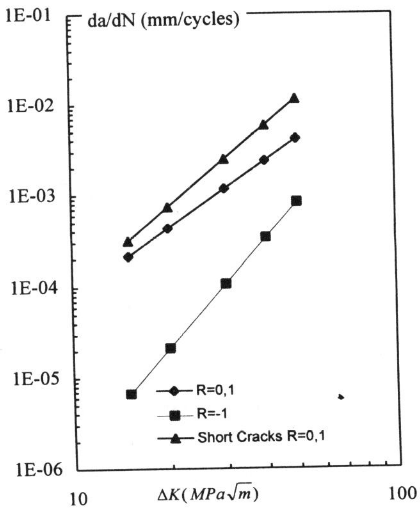

Figure 4: Fatigue crack growth rate versus ΔK for several R values.

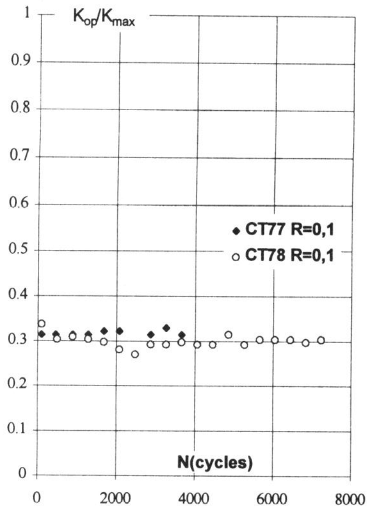

Figure 5:Relationship between K_{op}/K_{max} and N at R=0,1.

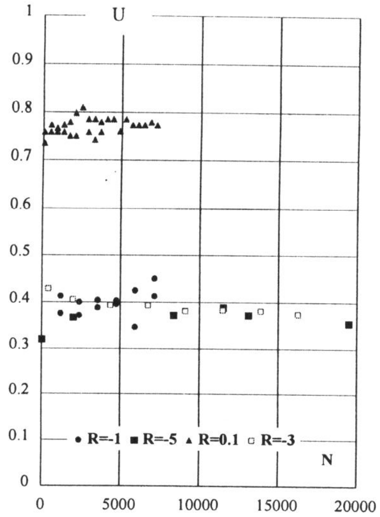

Figure 6: Variation of U during crack growth for various stress ratios R.

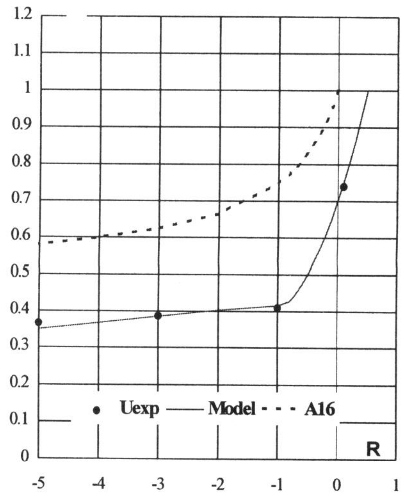

Figure 7: Comparison of U-R relationships.

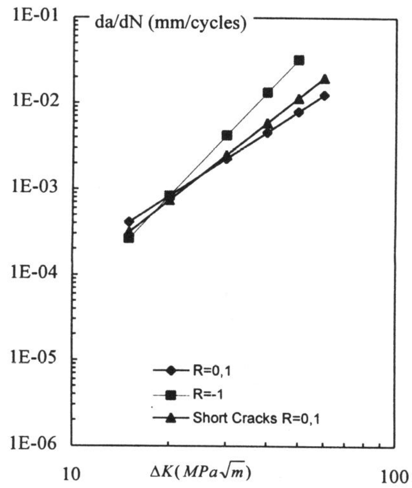

Figure 8: Fatigue crack growth rate versus ΔK_{eff} for several R values.