FATIGUE LIFE PREDICTION BASED ON MICROCRACK GROWTH

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The fatigue life of low alloy steels under random loading conditions can be predicted from the results of constant-amplitude tests to within an error of 30%. This is accomplished by defining the fatigue damage as the maximum crack length present. Thus, the fatigue life is obtained by integrating the appropriate crack growth law. In mild steel, the fraction of life required to initiate a continously growing crack is four times that of low alloy steel. The cracks nucleate in slip bands and grow in a "stop and go" manner up to a length of 60 μm (grain size is 20 μm), since grain boundaries and second phase particles hinder their propagation. When this behavior is approximated by a mean growth curve based on the effective cyclic J-integral, Z_{eff}, the life can be predicted to within an error of 50%.

INTRODUCTION

In engineering structures and components operating under cyclically varying loads fatigue failures are of major concern. Therefore, the most critical components, e.g. landing gear, are inspected at regular intervals. However, for a crack to be easily detected by standard methods of field inspection it must be about 1mm long. Then the growth of the crack can be followed and before it reaches a critical size the component in question is replaced. In order to design an efficient inspection schedule an accurate prediction for the number of cycles to form a 1mm sized crack, N_f, is needed. In many engineering alloys N_f is determined by the number of cycles required for a microcrack to grow from its initial length, typically 5-30 μm, to a length of 1mm. In this case the fatigue damage done to the material within every cycle is physically well defined and measurable in a laboratory experiment, i.e. the crack growth increment, Δa. If the appropriate crack growth law is known, Δa can be calculated for every cycle and the fatigue life is obtained by integrating the growth increments.

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The purpose of the present paper is to outline the essential features of a quantitative life prediction scheme based on a microcrack growth model (1,2). New experimental data on the growth of microcracks in a mild steel are presented and, together with the results of random loading tests, discussed in terms of the life prediction scheme.

BACKGROUND

The description of microcrack growth will be restricted to surface cracks in smooth specimens. Fig.1 illustrates that in low alloy steels cracks initiate at surface inclusions which have a typical size of 30 µm (2). This always occurs within the first 10% of the total life. The cracks grow with a constant depth to half surface length ratio, a/c, of 0.89. Raju and Newman (3) calculated the local stress intensity factor along the crack front of thumbnail surface cracks. Their results show that the stress intensity factor is constant along the crack front if a/c = 0.9, which is in good agreement with the experimental findings.

Since the propagating microcracks are embedded in plastified specimens, the linear fracture mechanics parameter, ΔK, is not applicable to correlate short crack growth data. For Masing-type materials whose cyclic stress-strain curve can be represented by the superposition of the elastic and plastic strain range,

$$\Delta\varepsilon_t = \Delta\sigma/E + C_1\, \Delta\sigma^n, \qquad (1)$$

the cyclic J-integral is the appropriate parameter to describe the growth of short cracks (4). For an elastic-plastic material the cyclic J-integral, which will be denoted by Z according to Wüthrich (4), may be obtained by adding the solutions for the small-scale yielding and the fully plastic limit (5),

$$Z = a\,(2.9\, W_e + 2.5\, W_p). \qquad (2)$$

W_e and W_p are taken from the hysteresis loop. In Masing-type materials, the hysteresis loop coincides with the cyclic stress-strain curve, eq.(1), so that

$$W_e = \Delta\sigma^2/2E \quad \text{and} \quad W_p = n/(n+1)\, C_1\, \Delta\sigma^{n+1}. \qquad (3)$$

Since no sophisticated techniques were used to detect crack opening and closure levels, Schijve's (6) equation for long cracks has been adopted as a crude approximation to account for crack closure effects. Since Schijve's formula is not applicable to compressive mean stresses we replaced it by

$$\Delta\sigma_{eff} = \Delta\sigma\, 3.72\, (3 - R)^{1.74} \qquad R = \sigma_{min}/\sigma_{max}, \qquad (4)$$

which approximates Schijve's formula for $R \geq -1$ and represents a reasonable extrapolation into the regime $R \leq -1$. Crack closure is assumed to influence only the elastic part of Z so that W_e has to be replaced by an effective value,

$$W_{e\ eff} = \Delta\sigma_{eff}^2/2E \tag{5}$$

and we have

$$Z_{eff} = a\ (2.9\ W_{e\ eff} + 2.5\ W_p). \tag{6}$$

The growth data for long and short fatigue cracks in low alloy steels were found to obey a power law (2),

$$da/dN = C_2\ Z_{eff}^{\ m}, \tag{7}$$

which reduces to the Paris law in the small-scale yielding limit, i.e. if $W_p = 0$. The right hand side of eq.(7) can be written as the product of a crack length dependant function and a function which depends on loading parameters and material properties,

$$da/dN = C_2\ a^m\ Z_D^{\ m} \tag{8}$$

$$Z_D = 2.9\ \Delta\sigma_{eff}^2/2E + 2.5\ n/(n+1)\ C_1\ \Delta\sigma^{n+1}. \tag{9}$$

In the form of eq.(8) the crack growth law is equivalent to the linear damage accumulation rule (Miner's law), i.e. by separating the crack length dependant part we gain a damage parameter, Z_D, which does not depend on the current state of damage (i.e. crack length) but only on the loading conditions. Integration of eq.(8) yields the fatigue life. For constant-amplitude loading one obtains

$$N_f = C_3\ Z_D^{\ -m} \tag{10}$$

$$C_3 = (C_2\ (1-m))^{-1}\ (a_f^{\ 1-m} - a_o^{\ 1-m}), \tag{11}$$

where a_o is the initial crack length, and corresponds to the inclusion size, and a_f = 1mm. For variable-amplitude loading, the lifetime is given by

$$\int_0^{N_f} (Z_D^{\ m}/C_3)\ dN = 1 \tag{12}$$

The damage parameter, Z_D, contains the stress range as well as the plastic strain range. For $\Delta\varepsilon_p >> \Delta\sigma/E$ eq.(10) is equivalent to Coffin-Manson's law for low cycle fatigue conditions. At the other limit, $\Delta\varepsilon_p << \Delta\sigma/E$, Z_D represents the proper damage parameter under conditions where the stress range governs the fatigue life.

Note that no adjustable parameters were used in deriving eq.(12) and that Z_D is obtained from the solution of elastic-plastic crack tip fields. By applying eq.(12) to low alloy steels fatigued under random loading conditions, the lifetime could be predicted within an accuracy of 30% (2).

EXPERIMENTAL PROCEDURES

The material chosen for this investigation was a mild steel (German grade St 37) with an average ferrite grain size of 20µm. For all experiments smooth tensile specimens were employed, the gauge sections being 16mm long and 8mm in diameter. In order to assure a consistent surface finish all specimens were electropolished and slightly etched to reveal the grain boundaries.

Fatigue testing was carried out in a computer controlled closed loop testing system in ambient air. Constant-amplitude tests were done under plastic strain and mean stress control, while incremental step tests and random load tests were done under total strain reversals. The cracks were allowed to initiate naturally by fatigue and their growth was monitored by replicating the specimen gauge section periodically (time period $\leq 0.05N_f$). The test was stopped when the main crack (i.e. the crack that would have lead to failure) reached a length of 1mm. Then the replica series was studied in reversed sequence to yield the entire crack growth history. Several specimens with cracks of different surface lengths, $300\mu m \leq 2c \leq 2000\mu m$, were broken in liquid nitrogen to measure the crack depth, a, and to determine the ratio a/c. In the above range the value of a/c was found to be independent of crack length and to coincide with the value of the low alloy steels (2), i.e. a/c = 0.89 .

RESULTS AND DISCUSSION

Cyclic Stress Strain Behavior

The application of a path-independent integral in fatigue crack growth studies requires that the strain increments are given by a unique function of the stress increments, both measured from the points of load reversal. Under the assumption that the material exhibits Masing-behavior and eq.(1) is the appropriate material law, eq.(1) will hold for all applied strain ranges and coincides with the shape of the hysteresis loop. Therefore, the saturated hysteresis loops have been measured in incremental step tests. Since the amount of cyclic softening in ferritic steels depends on the maximum strain range occurring in an incremental step test, several tests with different maximum strain ranges were carried out. Within one test the hysteresis loop had stabilized after the first loading block had passed. Fig.2 compares the shape of the hysteresis loops with the cyclic stress strain curve. Except for low strain ranges, where we find deviations from ideal Masing-behavior, the material law, eq.(1), describes well the cyclic deformation behavior of the mild steel.

Microcrack Growth

Microcrack growth studies were performed for plastic strain amplitudes $3\cdot10^{-4} \leq \Delta\varepsilon_p/2 \leq 10^{-3}$ and mean stresses σ_m=0 and 50 MPa yielding R-values of -1 and -0.5, respectively. The corresponding fatigue lifetimes varied between 47 kcy and 700 kcy. Figs.3 and 4 illustrate the essential features of microcrack growth behavior. The cracks initiate in slip bands and their growth temporarily stops when they hit the first grain boundary (fig.3) and/or phase boundary (fig.4). The time for crack initiation and growth within the first surface grain takes 15-25% of the total life, N_f, whereas slip bands are visible after 1% of N_f. When the crack continues to propagate into the neighboring grains and approaches the boundaries of the second grains another crack arrest occurs at the surface. Finally, after 40-45% of N_f, the microcracks exhibit a continous propagation behavior throughout the rest of the fatigue life. The complete growth history of the crack in fig.4 is summarized in fig.5. At the transition from 'stop and go' events to continous growth the crack lengths were 40-60µm, which is equal to 2-3 times the average grain size. The rumpled surface appearance in fig.4 is due to a tensile mean strain caused by the tensile mean stress of 50 MPa. Also, the mean stress causes a larger crack opening and, thus, allows the softened acetate sheet to infiltrate the crack during replication and to form distinct extrusions on the replica. However, the height or width of such an extrusion cannot be taken as a quantitative measure of the crack profile. Qualitatively, our observations agree with the findings of Wagner et al.(7) that the crack entirely penetrates the first grain before it extends to neighboring grains.

The solid line in fig.5 represents a least square fit of the integrated growth law, eq.(10), to the data obtained for $0.4 \leq N/N_f \leq 1$, with C_2, m and a_o being the adjustable parameters. Interestingly, the fit curve represents a reasonable approximation for the "stop and go" growth behavior below 40% of N_f (fig.5). In this manner the growth data obtained at different amplitudes and mean stresses were fitted and the individual curves are shown in fig.6. An average value of 13µm was obtained for a_o which corresponds to about one half of the grain size. The accordance of short and long crack growth rates indicates that Z_{eff} seems to be the appropriate parameter to correlate fatigue crack growth data in mild steel.

Life Prediction

Fig.7 shows a comparison of measured fatigue lifetimes with those calculated from eq.(10) with the parameters m, C_2 and a_o taken from measurements of microcrack growth rates. The data shown in fig.7 were obtained from tests in which the plastic strain amplitude was held constant. This corresponds to constant Z_D to within 5% since the stress amplitude does not vary substantially during a constant plastic strain amplitude test. The calculated line in fig.7 and the data can only be expected to agree if the fatigue lifetime is determined by microcrack growth rather than by crack nucleation. In fact, we found that nucleation occurs early in the fatigue life of mild steel. Calculated and measured lifetimes agree to within a factor 2.5. The greatest deviations occur in the tests with a tensile mean stress. In this case, the discrepancy arises from the fact that the solid line was calculated using an average value for C_2, whereas under a tensile mean stress the cracks tended to grow faster. In fig.6, the uppermost line represents such a test. Taking C_2 from the individual growth rate measurement reduces the discrepancy in fig.7 to a factor of 1.5. Fig.7 also shows deviations of the calculated line from the data in the low cycle fatigue regime. This could possibly be due to a decreasing effect of the retardation mechanism during early crack growth. But since crack growth under low cycle fatigue conditions has not been measured this reasoning lacks experimental verification.

The random load tests were performed by repeated block loading. Each block contained 1000 total strain reversals which were distributed according to a clipped exponential density function (8). The resulting distribution of strain peaks is approximately symmetric around zero. The lifetimes measured in these random load tests are compared with predictions made by eq.(12) with m, C_2 and a_o inserted from crack growth measurements. The calculations included a rain flow analysis to account for the cyclic memory effect and were done in two different ways represented by open and closed symbols in fig.8. On the one hand, the stress response of the material to the applied total strain was calculated from the relation given in fig.2. On the other hand, the stress response was measured, and it can be seen from fig.8 that the two values differ only slightly. A comparison of measured and predicted fatigue lives shows good agreement for $N_f > 300$ kcy (fig.8). As could be expected from constant amplitude data, larger deviations occur in the lower fatigue life regime. Nevertheless, the difference between prediction and experiment is only 50% in the worst case.

CONCLUSIONS

1. In mild steel crack nucleation occurs within the first 20% of total life.
2. For crack lengths smaller than 2-3 average grain sizes a "stop and go" growth behavior is observed.
3. In an average sense the growth rate can be described by a power law, $da/dN \propto Z^m_{eff}$.
4. The mean stress effect is not described accurately.
5. The fatigue lives under random loading conditions can be predicted to within an error of 50%.

REFERENCES

(1) Neumann, P., Heitmann, H.H. and Vehoff, H., "Ermüdungsverhalten Metallischer Werkstoffe", Edited by D.Munz, Informationsgesellschaft, DGM, 1985, pp.167-184

(2) Heitmann, H.H., Vehoff, H. and Neumann, P., Proc. ICF6, New-Dehli, India, 1984

(3) Raju, I.S. and Newman, J.C., Engng.Frac.Mech., Vol.11, 1979, pp.817-829

(4) Wüthrich, C., Int.J.Frac., Vol.20, 1982, pp.R35-R37

(5) Shih, C.F. and Hutchinson, J.W., ASME J.Engng.Mat.Techn., Vol.98, 1976, pp.289-295

(6) Schijve, J., Engng.Frac.Mech., Vol.14, 1981, pp.461-465

(7) Wagner, L., Gregory, J.K., Gysler, A. and Lütjering, G., Proc. Sec. Int. Work Shop on "Small Fatigue Cracks", Santa Barbara, USA, 1986

(8) Polak, J. and Klesnil, M., Fat.Engng.Mat.Struc., Vol.1, 1979, pp.123-133

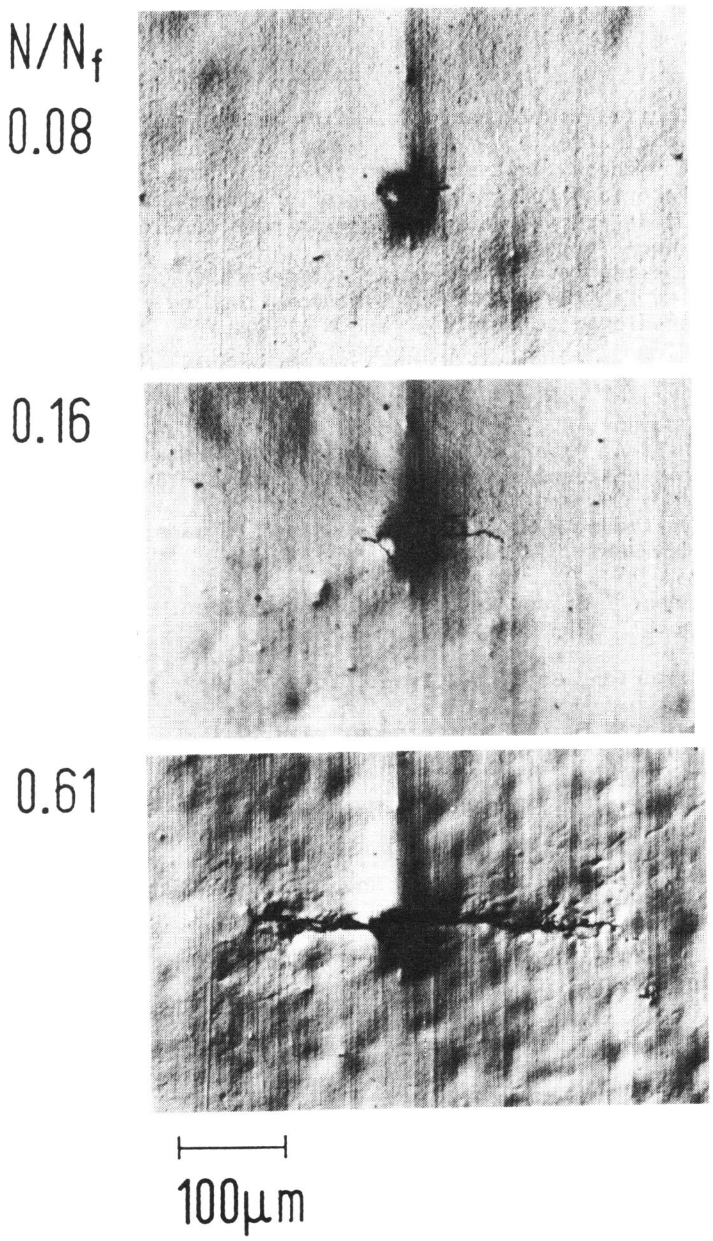

Figure 1 Microcrack growth in low alloy steel StE 460 (specimen axis is vertical)

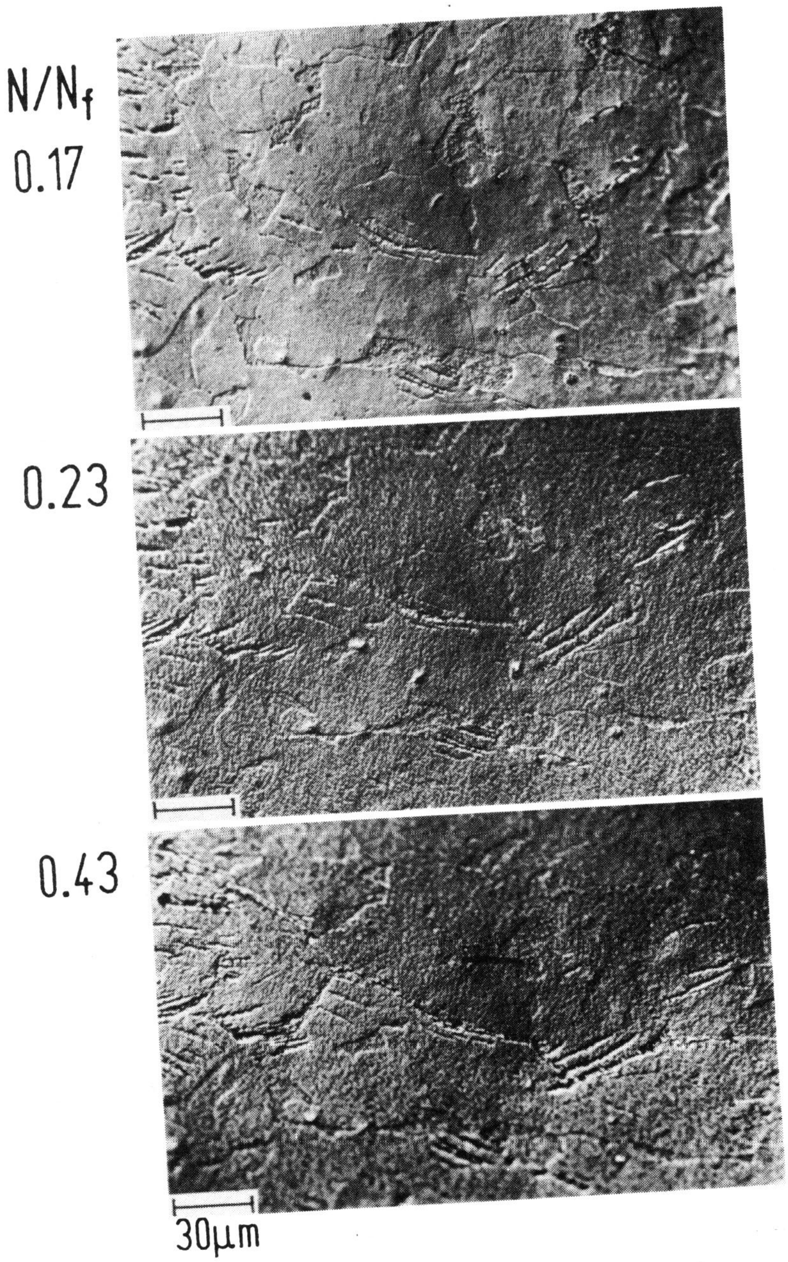

Figure 3 Microcrack growth in mild steel at R=-1 (specimen axis is vertical)

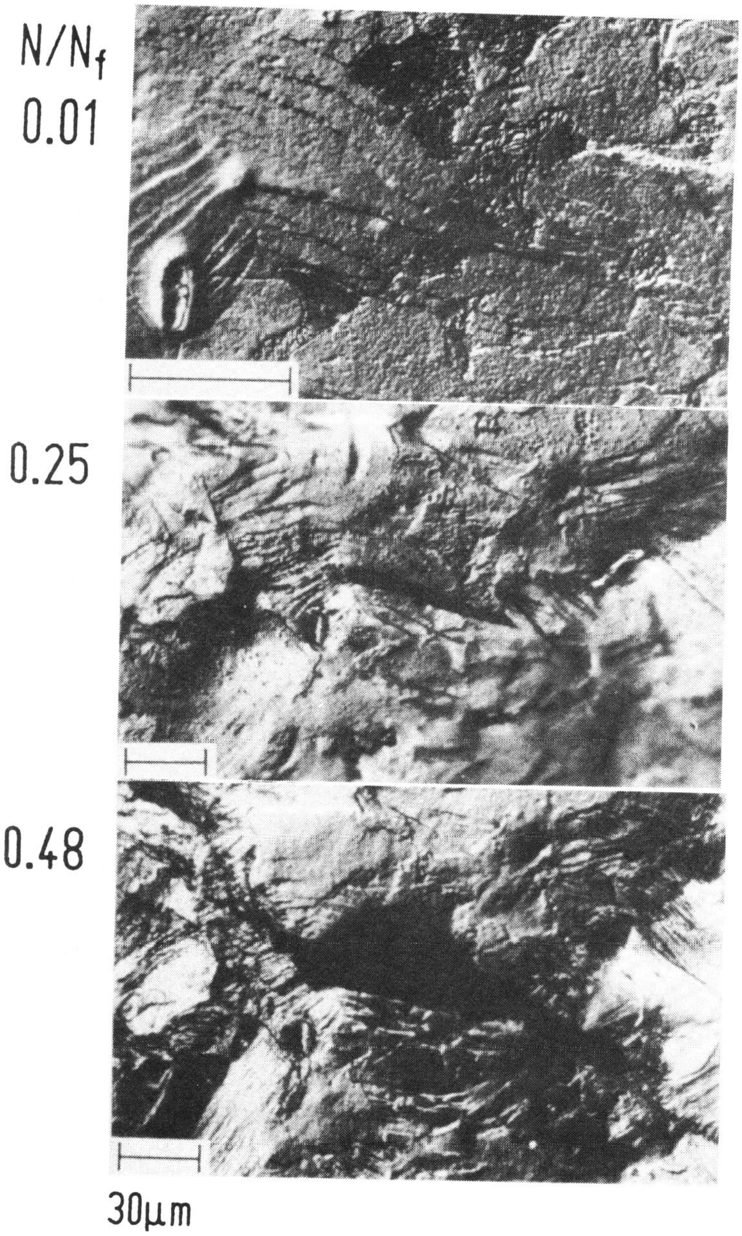

Figure 4 Microcrack growth in mild steel at R=-0.5 (specimen axis is vertical)

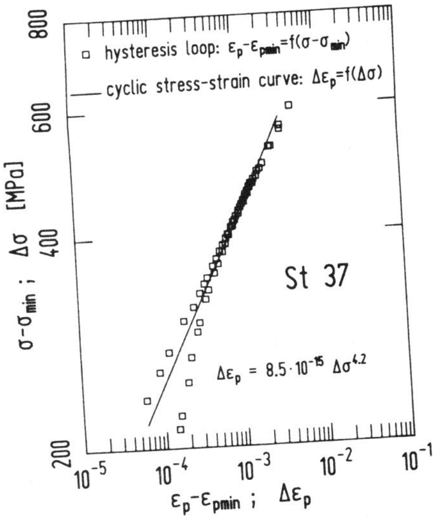

Figure 2 Cyclic stress strain behavior of mild steel

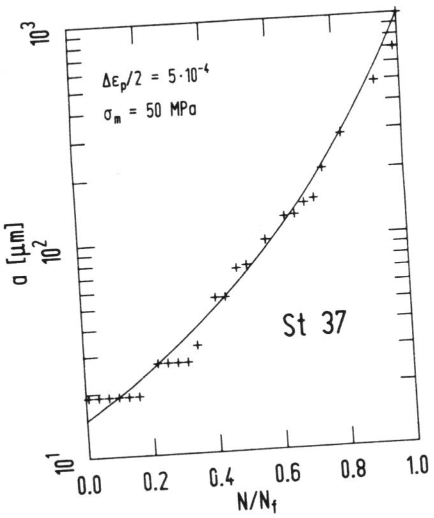

Figure 5 Retardation behavior of crack in fig.4 (N_f=130 kcy)

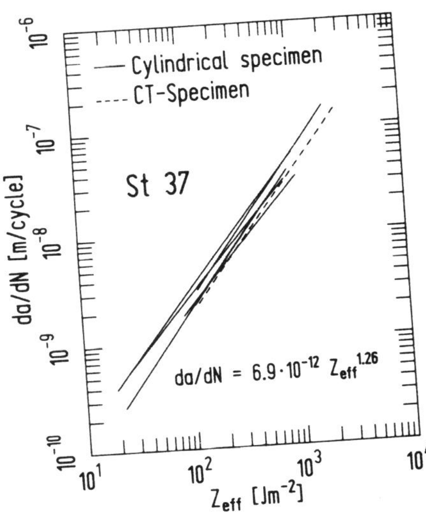

Figure 6 Fatigue crack growth rates vs Z_{eff}

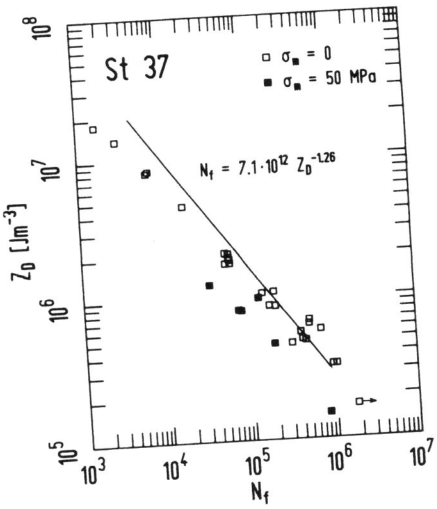

Figure 7 Fatigue lives as a function of damage parameter Z_D

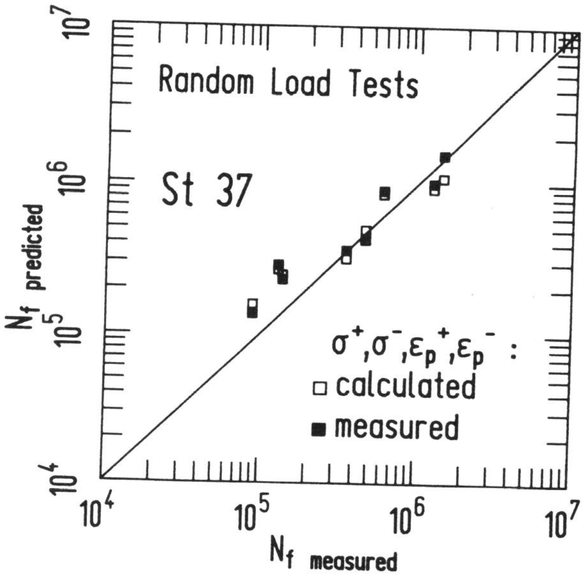

Figure 8 Predicted and experimentally determined fatigue lives