A DISCUSSION OF MECHANISMS OF ACCELERATED AND RETARDED FATIGUE CRACK GROWTH

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ABSTRACT

The relevance of the effective stress intensity range to crack growth is considered for constant and for variable amplitude loading. The accelerated and retarded growth associated with simple programmed loadings is reported for two steels and an aluminium alloy. The load interaction effects are due to several competing mechanisms, and not due to the single, popular mechanism of crack closure.

KEYWORDS

Crack closure, DC technique, fatigue life prediction, fatigue micromechanisms, microcomputer control, variable amplitude fatigue.

HISTORICAL OVERVIEW

The early observations of crack closure by Elber (1971) have prompted much research into load sequence effects associated with variable amplitude loading. For instance, the retarded growth due to a single peak overload has been studied intensively. Recently, interest has been shown in load sequences which cause accelerated growth. Crack closure has met with some success in accounting for these load interaction effects; by correlating crack growth with that part of the applied stress intensity range for which the crack is open, ΔK_{eff}, we may account for both retarded and accelerated growth.

In the near threshold regime, closure ideas have also played an important role in explaining the influence of mean stress, environment and material strength on growth rate. Because no simple design rules have been forthcoming to enable ΔK_{eff} to be calculated from material properties, the use of closure in design has been limited.

It is with the above developments in mind that an extensive programme of experiments has been undertaken into the accelerated and retarded crack growth response of low strength steels and an aluminium alloy. The purpose of this paper is to outline the results for the case of periodic overloads and periodic underloads. The possible mechanisms promoting accelerated and retarded growth are summarised in the light of these test results.

EXPERIMENTAL

Programmed loading of the type defined in Fig. 1 was applied to 50 mm wide and 3 - 24 mm thick compact tension specimens, made from BS4360 50B structural steel, BS1501 32A pressure vessel steel and 2014A-T4 aluminium alloy. The yield stresses of the BS4360 50B steel, BS1501 32A steel and 2014A-T4 aluminium alloy were 352 MPa, 388 MPa and 325 MPa, respectively. The steel specimens were stress-relieved for 1 hour at 650°C prior to testing, while the aluminium specimens were tested in the as-received condition.

Crack advance was monitored using the DC potential drop method. During each

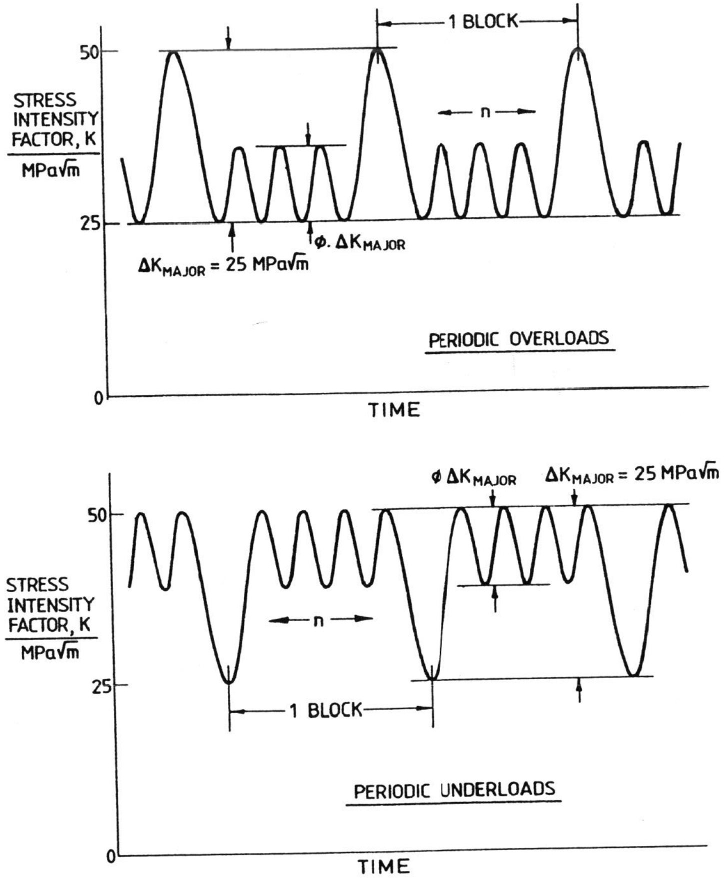

Fig. 1: Definition of load histories used in present study

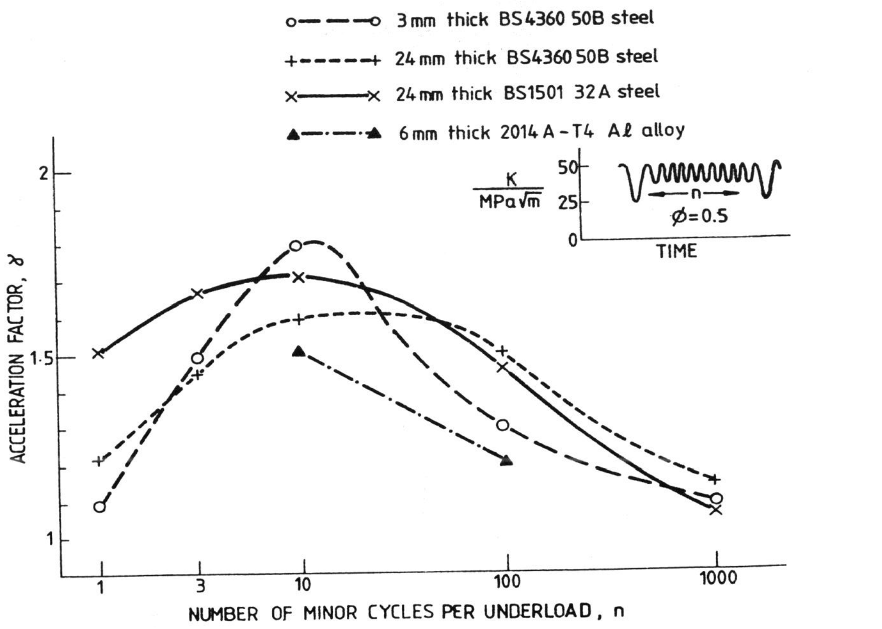

Fig. 2: Acceleration effect due to periodic underloads. Acceleration factor, γ, vs. number of minor cycles, n.

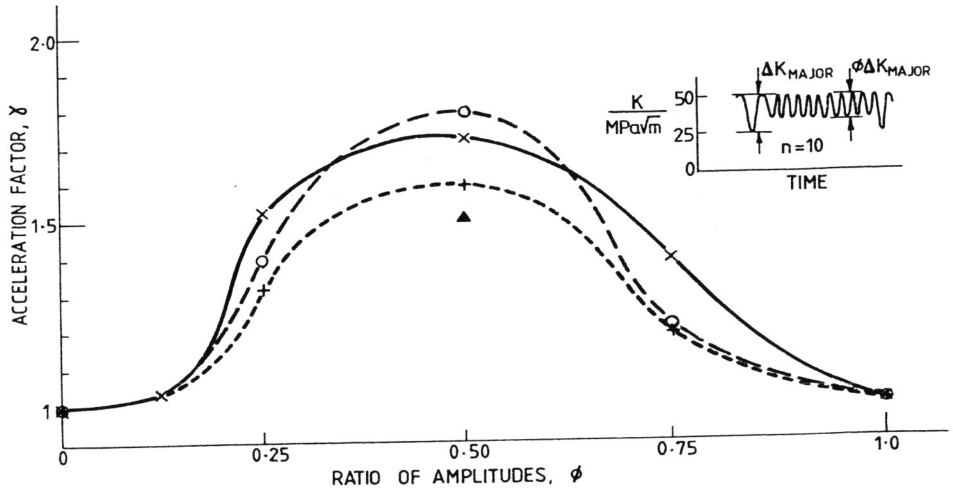

Fig. 3: Acceleration effect due to periodic underloads. Acceleration factor, γ, vs. ratio of amplitude, ϕ.

test, loads were automatically shed to maintain K-control and yield constant crack growth rates. Full details of the microcomputer control system are given in Fleck and Hooley (1983). K-control was used in order to reduce scatter in measured growth rates from a factor of 2, typical for tests performed in load control, to ± 5% (Fleck, 1983).

RESULTS

The effects of varying the number, n, and amplitude, ϕ, of minor cycles for the periodic underload tests are given in Figs. 2 and 3. Results are normalised by defining an acceleration factor, γ, such that

$$\gamma = \frac{\text{measured growth rate per block}}{\text{growth rate per block assuming linear summation of damage}}$$

Accelerated growth occurs in every case. Maximum acceleration occurs when n = 10 and ϕ = 0.5, for all types and thicknesses of material; cracks grow 50 - 80% faster than would be expected on the basis of a linear summation of damage.

The effect of varying the number, n, of minor cycles per overload is displayed in Fig. 4. The acceleration factor, γ, monotonically decreases from about 1.2 to about 0.6, when n is increased from 1 to 1000.

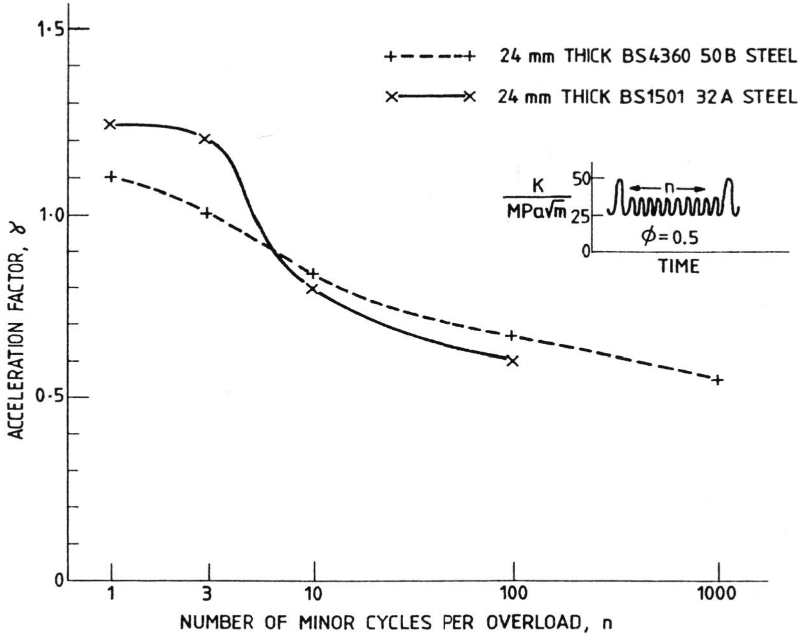

Fig. 4: Acceleration effect due to periodic overloads. Acceleration factor, γ, vs. number of minor cycles, n.

DISCUSSION OF MECHANISMS LEADING TO ACCELERATED AND RETARDED GROWTH

Observations of accelerated growth were made as early as 1966, when Schijve and de Rijk (1966) investigated the effect of "ground-to-air" cycles on the crack propagation response of 2024-T3 aluminium alloy. They considered periodic underloads with n = 10 and ϕ = 0.5; the load ratio (= minimum load/maximum load) of their underloads was about zero, compared with 0.5 in the present study. Schijve and de Rijk found that cracks grew about 15% faster than a linear summation model would predict. Hsu and Lassite (1974) have also conducted periodic underload tests on an aluminium alloy, 7050-T73 and a titanium alloy, Ti-6Al-4V. The load ratio of each underload was - 1.5. Cracks were found to grow in the aluminium alloy at a rate 20% faster than predicted by a linear summation of growth. No load interaction effect was observed for the titanium alloy. It appears that accelerated growth due to periodic underloads is shown by a variety of aluminium alloys and steels but not by Ti-6Al-4V.

It is surprising that periodic overloads give rise to accelerated growth for minor cycles n ≤ 3 and retarded growth for n > 3, Fig. 4. The results suggest a competition of mechanisms leading to accelerated and retarded growth. Support for the present results may be found in the literature: Broek and Leis (1981) observed that periodic overloads with a small number of minor cycles, n, gave rise to accelerated growth, while Stephens et al (1977) found that periodic overloads with a large n led to retarded growth.

The possible mechanisms causing accelerated and retarded growth are summarised in Table 1. Each mechanism is briefly discussed in turn.

(i) Crack closure measurements using crack tip clip gauges, crack mouth gauges and back face strain gauges showed that the crack was fully open for all underload and overload tests. Thus, crack closure, 1, does not explain the accelerated or retarded growth observed in the present study, see Table 1.

(ii) Observations of striation spacings on the fatigue fracture surfaces indicated that accelerated or retarded growth accompanied the minor cycles rather than the underload or overload. The crack advance mechanism was the same as for constant amplitude loading, ruling out explanation 2.

(iii) Crack tip replicas were taken at each load reversal of a program block, for several of the tests. An examination of the crack tip profile revealed that accelerated growth was not due to crack tip sharpening by the underloads or overloads. Retarded growth may be partly caused by crack tip blunting associated with each of the periodic overloads, mechanism 3.

(iv) An underload or overload leads to pre-strain of material ahead of the crack tip, the exhaustion of its ductility, and the possibility of accelerated growth, 4 (Fleck, 1984). Concurrently, the major cycle causes strain hardening ahead of the crack tip, and thereby leads to smaller plastic strains ahead of the crack tip and to slower crack growth, 5.

(v) An increasing body of evidence, e.g. Garrett and Knott (1976), indicates that crack advance is governed by cyclic displacements at the crack tip rather than damage accumulation in the reversed plastic

TABLE 1: Possible Mechanisms Causing Accelerated and Retarded Growth

	Accelerated growth due to periodic underloads	Accelerated growth due to periodic overloads (n ≤ 3)	Retarded growth due to periodic overloads (n > 3)
1 Crack closure	×	×	×
2 Change in the crack growth mechanism and dislocation structure near the crack tip, due to the major cycles	×	×	×
3 Crack tip sharpening or blunting	×	×	√
4 Pre-strain of material ahead of the crack tip due to the major cycles. Leads to faster crack growth	√	√	×
5 Strain hardening ahead of the crack tip due to the major cycles	×	×	√
6 Change in rate of damage accumulation in the reversed plastic zone ahead of the crack tip	×	×	×
7 Cyclic hardening or softening in the reversed plastic zone ahead of the crack tip	×	×	×
8 Influence of mean stress on the crack growth mechanism	√	×	√

√ - may be operative
× - discounted

zone ahead of the crack tip. Thus, explanation 6 is discounted.

(vi) It has been suggested that retardation effects are due to cyclic hardening at the crack tip. Since BS4360 50B is cyclically stable, we cannot appeal to this mechanism, 7.

(vii) Under constant amplitude loading, the mean stress ahead of a crack tip relaxes to zero by cyclic creep (Saxena and Hudak, 1979). For the case of perioic underloads, it is possible that the mean local stress associated with the underloads relaxes to zero, leaving the mean stress associated with the minor cycles at a tensile level. Accelerated growth may then accompany the minor cycles. By a similar argument, periodic overloads would give rise to retarded growth, 8.

It is apparent from Table 1 that no single mechanism can account for the load interaction effects observed in the present study. Several competing mechanisms are in operation.

CONCLUDING DISCUSSION

Crack growth phenomena, as outlined in the present study, influence growth rates by less than a factor of 2. Such small changes in growth rate fall within the scatter band associated with conventional da/dN against ΔK plots, and so can be ignored for design and predictive purposes. Retardation phenomena, due to a single peak overload or periodic overloads, usually lead to a conservative estimation of fatigue life and so can also be ignored for many design situations. It is often clear from examination of the load history whether retardation is expected or not.

Load interaction studies are, however, very useful for clarification of the manner in which a crack advances. Results of the present study show how complicated the mechanisms are for even simple load histories. Elucidation of these subtle load interaction phenomena is only possible when highly developed experimental techniques are employed.

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