Brittle Cracking Processes during Fatigue Crack Propagation

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Introduction Fatigue crack propagation rates under linear elastic conditions are usually well represented by an equation of the form:

$$^{da}/_{dN} = C\Delta K^m \qquad (1)$$

where $^{da}/dN$ is the growth rate, C and m are constants and $\Delta K = K_{max} - K_{min}$, where K_{max} and K_{min} are extreme values of stress intensity during each cycle. For many materials and loading conditions, m has a value of between 2-4, consistent with propagation by fatigue "striations" giving one growth increment per cycle. In such situations equation (1) can be used with confidence to predict growth rates in service components and to provide the basis for design against failure by fatigue. In other cases, it is found that the growth rate is markedly increased by a superimposed mean tensile stress or that the exponent, m, increases dramatically in a particular material or heat-treated condition. Our paper presents results on two materials in which the incidence of brittle cracking during fatigue gives rise to both these effects, and a body of previous results is examined to show that the occurrence of monotonic fracture modes could similarly be responsible for the more general behaviour.

Fatigue tests have been carried out at 20 Hz in air (55% humidity) at 20°C, using notched specimens deformed in four-point (pure) bending, using a servo-hydraulic machine under load control. Growth rates have been continuously monitored using highly sensitive electrical potential techniques.

Intergranular Fracture during Fatigue in a Low-Alloy Steel Specimens were prepared from a low-alloy steel, En30A (0.35%C, 4.23%Ni, 1.43%Cr) which was produced in the temper-embrittled and unembrittled conditions by suitable heat-treatment. The room-temperature tensile properties of the steel remain unaffected by the embrittlement, but it induces brittle intergranular failure in a fracture toughness test. Fatigue tests were carried out in both conditions at a constant initial ΔK for a variety of mean stresses. Results given in fig. 1, where R denotes the stress ratio K_{max}/K_{min}, show the basic variation of crack length with number of cycles. It is apparent that the cracks grow more quickly in the embrittled condition, particularly at high mean stresses. The crack growth rates were derived from the curves in fig. 1 by numerical differentiation and are shown in fig. 2 as a function of ΔK. There is little or no effect of mean stress on growth rate for the unembrittled steel and the slope, m, is virtually constant (2.4). In contrast, for the embrittled condition, growth rates are extremely sensitive to mean stress and show an apparently marked increase of slope from 2.7 to 5.8 as R increases from 0.05 to 0.50. Scanning electron microscopy revealed that the mode of propagation in the unembrittled steel was predominantly by the usual fatigue striation mechanism. In the embrittled condition, a proportion of brittle intergranular fracture was observed in association with the striations. The incidence of such fracture increased with mean stress level and, at high levels, occurred additionally as large bursts which give rise to the discontinuities in the crack length (fig. 1) and crack growth rate (fig. 2) curves.

Cleavage Fracture during Fatigue in a Mild Steel Similar effects have been observed in a high-nitrogen mild steel (0.07%C) when fatigued above and below the ductile-brittle transition temperature (T). Fatigue tests on fine-grained material (28μ) at 20°C (> T) showed that the propagation rate was insensitive to mean stress for the range studied, and that the mechanism of growth was almost entirely by ductile striations. In contrast the mode of crack growth in 60μ grain size at 20°C (< T) was found to include segments of cleavage, the frequency and magnitude of which increased with K_{max} such that the overall propagation rate and the slope, m, were markedly sensitive to mean stress, (fig. 3).

Discussion In our experiments, it was found that effects of mean stress on growth rate and slope, m, were produced only when some mode of brittle fracture occurred in addition to ductile fatigue striations. Similar effects may also be attributed to the incidence of regions of fibrous fracture. The onset of brittle fracture is most likely to occur in materials of low static fracture toughness and we therefore conclude that high slopes and effects of mean stress are to be found in such materials. In fig. 4 we have accumulated data for a variety of steels which show the dependence of m on static toughness, K_{Ic}. It is clear that m is sensibly independent of K_{Ic} for values above about 60 $MNm^{-3/2}$, but that a large scatter of slopes, from 2-10, is found below this figure. The scatter is likely to arise from differences in brittle cracking mechanisms. We postulate that effects of mean stress on growth rates under linear elastic conditions will predominate in brittle materials. An effect of this sort has, indeed, been observed in aluminium alloys, as well as in our own results.

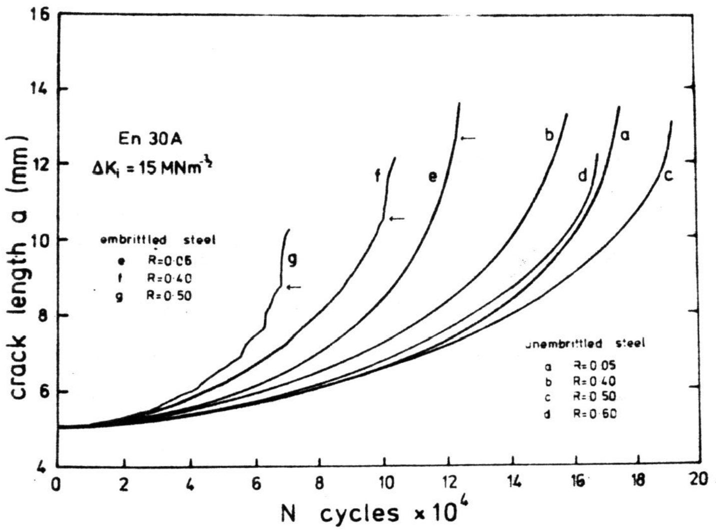

Fig. 1 Crack length curves for unembrittled and embrittled low alloy steel for a range of R values 0.05–0.60.

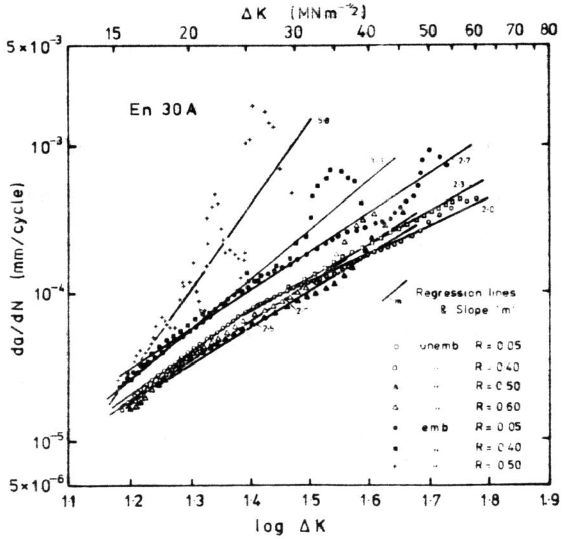

Fig. 2 Variation in crack growth rate ($^{da}/dN$) with alternating stress intensity (ΔK) for unembrittled and embrittled low alloy steel.

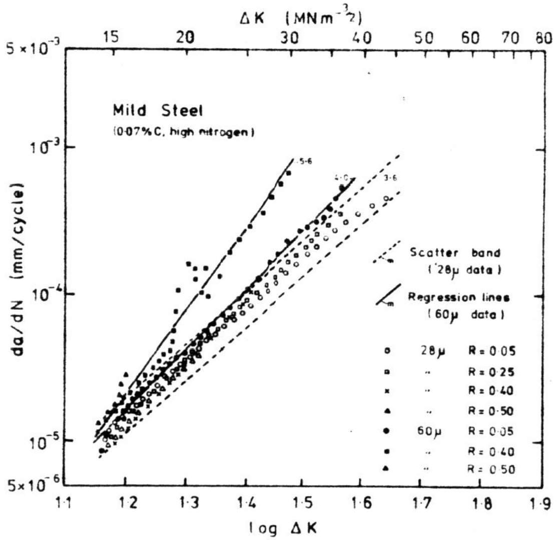

Fig. 3 Variation in crack growth rate ($^{da}/dN$) with alternating stress intensity (ΔK) for high-nitrogen mild steel with 28μ and 60μ grain size.

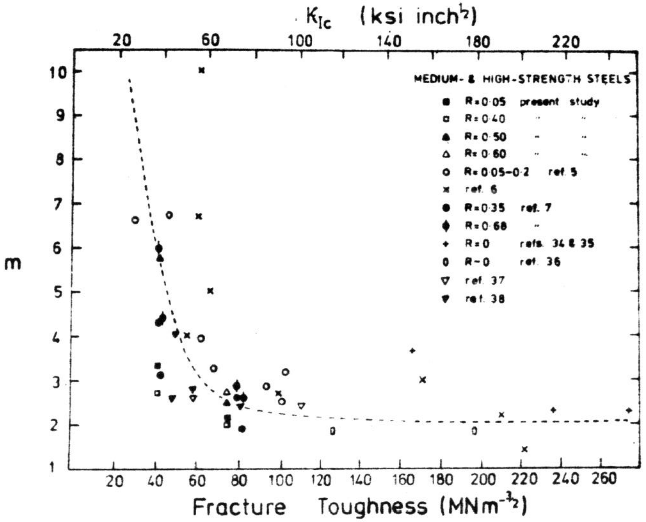

Fig. 4 Variation of exponent 'm' from equation (1) with static fracture toughness K_{Ic}. Detailed references given in "Mechanisms of Fatigue Crack Growth in Low Alloy Steel", R.O. Ritchie and J.F. Knott, submitted to Acta Metallurgica.