FATIGUE CRACK GROWTH IN A HIGH STRENGTH STEEL

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INTRODUCTION

Many factors in addition to the stress intensity factor range can have a significant effect on fatigue crack growth. For a mild steel, EN3A, it has been shown [1] that the parameters K_{max}, K_c and ΔK_{th} can be successfully incorporated into a general fatigue crack growth equation as:

$$\frac{da}{dn} = C\left[\frac{\Delta K-\Delta K_{th}}{K_C-K_{max}}\right]^n + C' \qquad (1)$$

where C and C' are constants, the value of C' is taken as the lattice spacing per cycle.

To examine the more general applicability of equation (1) a high strength steel EN24 was used to provide data for two crack growth directions. The material provides a contrast to the mild steel in that it exhibits high values of σ_f, σ_y, and low ductility. The value of K_C depends strongly on material test orientation although σ_f, σ_y and ductility are similar along and across the grain.

EXPERIMENTAL WORK

Compact tension specimens of 1T geometry were made from 25 mm and 10 mm thick plates. These were solution treated for 1 hour at 835°C, oil quenched and tempered at 500°C for 1 hour. This treatment produced a tempered martensite structure. The mechanical properties and chemical composition are given in Table 1.

The specimen material orientations were designated A and B. The grain flow was perpendicular to the crack growth direction for A and parallel to crack growth direction for B. Orientations A and B had similar mechanical properties except for fracture toughness where K_C = 95 MPa$\cdot$m$^{1/2}$ for A and 47 MPa$\cdot$m$^{1/2}$ for B.

Fatigue crack growth rates were determined using standard techniques [1], [2] for both constant ΔK, K_{mean} tests and constant stress ratio, ΔK increase tests. Growth rates were measured for the ΔK range 2-60 MPa$\cdot$m$^{1/2}$ for K_{mean} of 7-30 MPa$\cdot$m$^{1/2}$ and R = 0.0-0.75. Determinations of threshold range ΔK_{th} were made for orientation A by using an automatic load decrease displacement maintaining system [3]. Load reductions of 1% - 6% are triggered by crack opening displacement increments of approximately .0004 mm so that load is gradually reduced as the crack grows. Normally crack arrest occurs in approximately 20 x 10^6 cycles or less.

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EXPERIMENTAL RESULTS

Threshold and Growth Rates

The growth rate data are shown in Figure 1 for orientation A across the grain and in Figure 2 for orientation B along the grain. Growth rates for B are up to 4 x greater than A for comparable stress intensity factor ranges. The solid lines shown in Figures 1 and 2 were derived from equations (2) and (3). Crack growth was shown to occur for orientation B at the very low value of $\Delta K = 2$ MPa•m$^{1/2}$, for $K_{mean} = 25$ MPa•m$^{1/2}$. The measured growth rate of 9.5×10^{-11} m/cycle is less than the lattice spacing/cycle of $\sim 3 \times 10^{-10}$ m/cycle. This has been proposed [4] as a lower limit to purely mechanical fatigue crack growth and is generally true for a wide range of metals. Determinations of threshold ΔK_{th} showed that the normal crack arrest behaviour was not exhibited by EN24 steel. Cracks continued to grow very slowly at endurances of up to 74×10^6 cycles and at rates of 10^{-10} to 5×10^{-12} m/cycle. A typical crack length/endurance plot is shown Figure 3 with mild steel for comparison. The values of ΔK_{th} obtained depend on the endurance to which testing continues for the EN24. ΔK_{th} results at approximately the lattice spacing/cycle rate are shown in Figure 4 with other results for high strength steels, [4], [5]; and mild steel [1] for comparison. Growth rates determined from plots such as Figure 3 are included in Figure 1 which shows that there may be a slope change at about the lattice spacing/cycle rate. These growth rate results from the ΔK_{th} tests have not been used in the following rate data analysis.

Laboratory air is thought to be an agressive environment for this steel and so contributes to crack growth. Evidence for this view obtained from ΔK_{th} tests and surface fractography is discussed later.

Analysis of Propagation Rate Data

The data plotted in Figures 1 and 2 were analyzed to examine the fit of equation (1). The ΔK_{th} values used from Figure 4 were assumed to be true thresholds where growth does not occur below the lattice spacing/cycle rate. This rate was taken as $C' = 3 \times 10^{-10}$ m/cycle.

Analysis of the data yielded equations:

For orientation (A) $K_C = 95$ MPa•m$^{1/2}$

$$\frac{da}{dn} = 5 \times 10^{-7} \left[\frac{\Delta K - \Delta K_{th}}{95 - K_{max}}\right]^2 + 3 \times 10^{-10} \qquad (2)$$

For orientation (B) $K_C = 47$ MPa•m$^{1/2}$

$$\frac{da}{dn} = 1.7 \times 10^{-7} \left[\frac{\Delta K - \Delta K_{th}}{47 - K_{max}}\right]^2 + 3 \times 10^{-10} \qquad (3)$$

The equations adequately describe the effects of K_{max} and K_C and are used to predict the data as shown in Figures 1 and 2.

Fracture Surface Examination

Fracture surface examination using a scanning electron microscope showed that the steel exhibits a structure sensitive mode of cracking dependent on ΔK. Figure 5 shows examples of the fracture modes and the occurrence of the corrosion products previously mentioned. For $\Delta K \leq 3$ MPa•m$^{1/2}$ failure occurs by a relatively flat featureless mode which is transgranular with respect to the prior austenite grains. For $\Delta K = 3 - 20$ MPa•m$^{1/2}$ the incidence of an intergranular failure component increases to reach a peak and then decreases until at $\Delta K > 24$ MPa•m$^{1/2}$ it is absent. The normal ductile striation mechanism then occurs until fast fracture. A significant feature of the low ΔK and ΔK_{th} tests is the observation of corrosion or oxidation products on the fracture surfaces. This has a 'rust like' appearance and has also been observed for low ΔK and low R tests on EN 24 and a pearlite steel [5].

DISCUSSION

For EN24 steel fatigue crack growth rates depend on crack orientation. Crack growth rates along the grain were $\sim$ x 4 faster than across the grain for comparable stress intensity ranges. This effect can be expected as the crack front traverses a greater area of slag and nonmetallic inclusions along the grain than across the grain.

The crack growth results can be represented by the equation

$$\frac{da}{dn} = C \left[\frac{\Delta K - \Delta K_{th}}{K_C - K_{max}}\right]^2 + C'$$

where C and K_C depend on material orientation.

It is interesting to note that the exponent of the term

$$\left[\frac{\Delta K - \Delta K_{th}}{K_C - K_{max}}\right]$$

is two which agrees with the value found by Priddle [1] for EN3A mild steel.

The results for EN24 differ from many materials in that a well defined value of ΔK_{th} does not occur for laboratory air environments. Growth rates at $\Delta K < 2$ MPa•m$^{1/2}$ are less than the lattice spacing/cycle rate which was considered [4] to be a limit for purely mechanical crack growth. Very low growth rate behaviour has also been observed for an aluminum alloy in air [6], copper in air and mild steel in brine [7]. The surface oxidation and corrosion products present in the EN24 tests indicates that a corrosive component is significant below normal growth rates. This observation is important and it should be recognized that this behaviour may need to be allowed for in low stress vibration situations for materials and environments not yet experimentally investigated.

The occurrence of the intergranular mode of fracture has been observed by several investigators for EN24 steel [5], [8]. In general the extent of this mode depends on ΔK and is relatively independent of mean stress for a particular material condition. The presence of this mode also depends on the environment and is suppressed in vacuum. The ΔK value corresponding to peak % intergranular failure occurs when the alternating plastic zone size is dimensionally similar to the grain size. This has been shown for EN24 and titanium alloys [5], [9] and for a transgranular apparent cleavage mode in 316 stainless steel [10].

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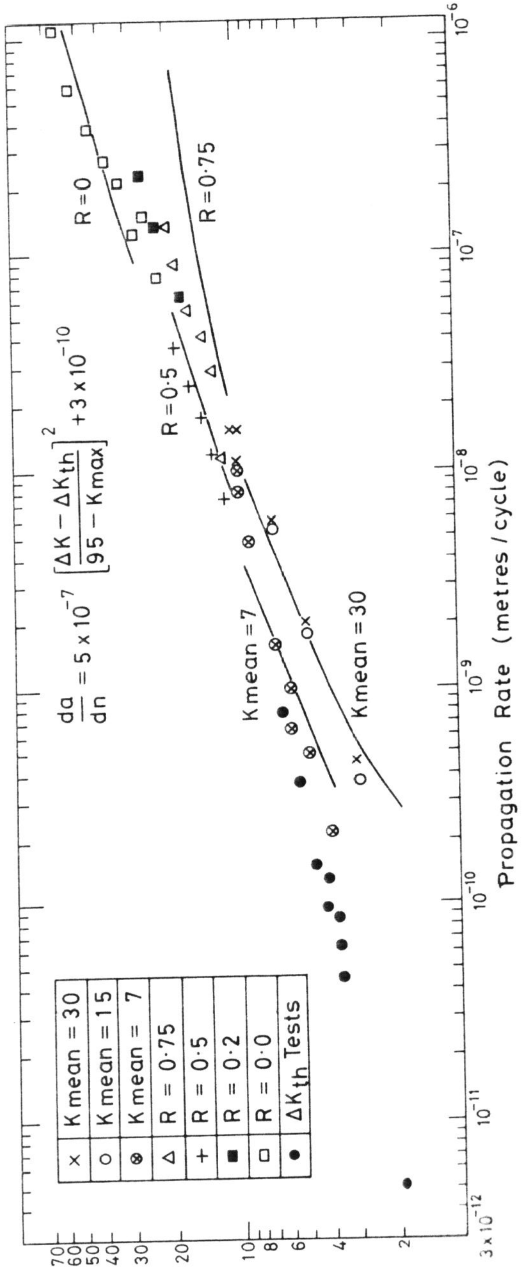


Figure 1 Crack Growth Data and Calculations for Orientation A

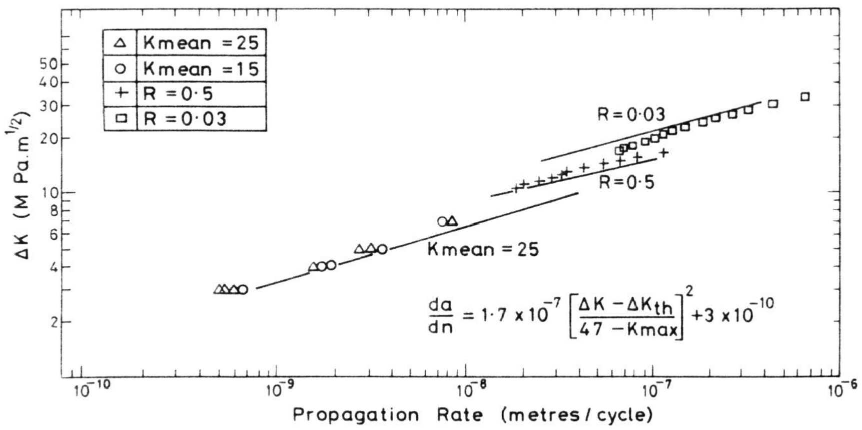


Figure 2 Crack Growth Data and Calculations for Orientation B

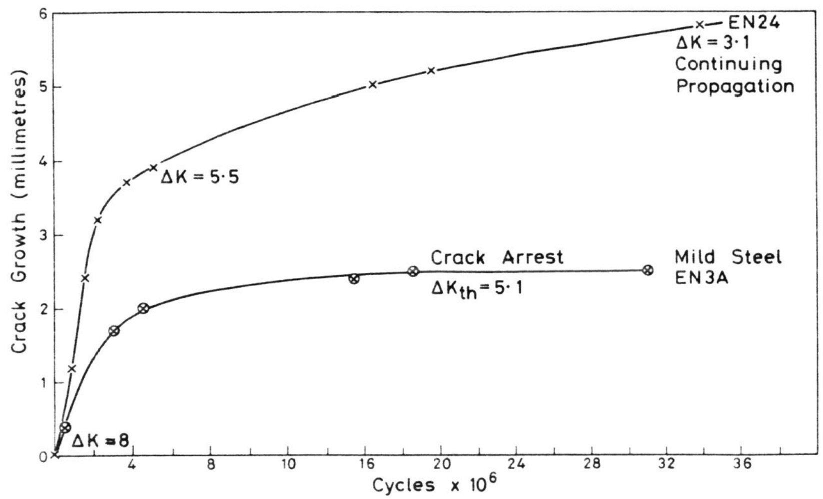


Figure 3 ΔK_{th} Test. Crack Length Against Endurance

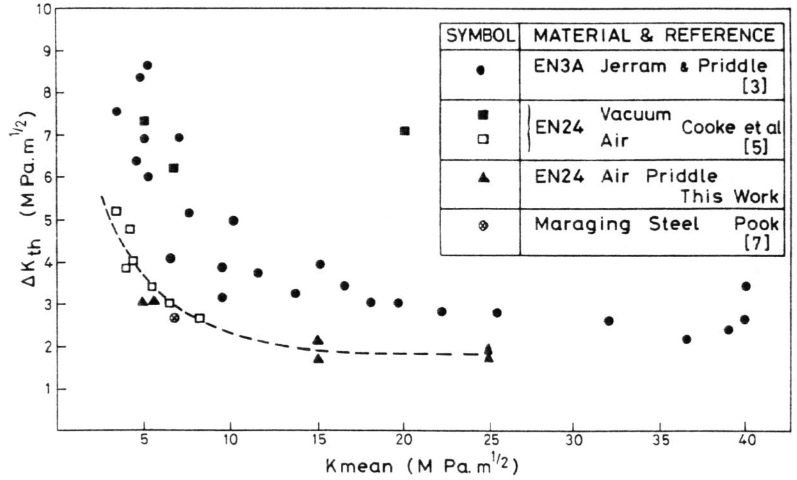
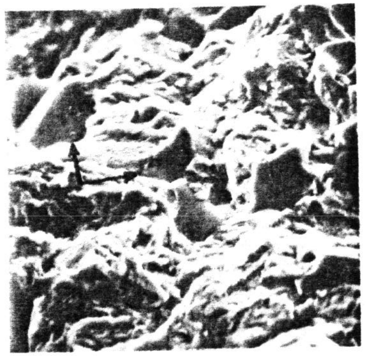
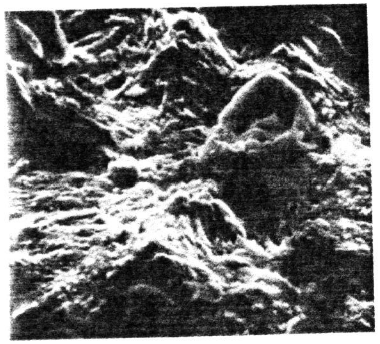


Figure 4 ΔK_{th} Data

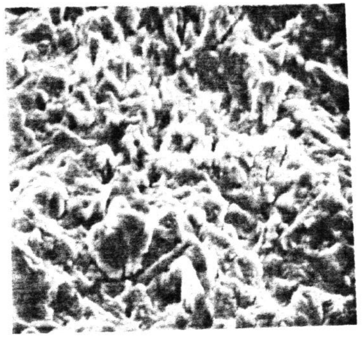
Flat Transgranular Surface
$\Delta K = 3$, $K_{MEAN} = 30$ x 700



Intergranular Facets
$\Delta K = 10$, $K_{MEAN} = 30$ x 700



Rust Like Corrosion Product
ΔK_{th} Test x 1000



Ductile Fracture
$\Delta K = 32$, $K_{MEAN} = 16$ x 600

Figure 5 Examples of Fractographic Features

Table 1 Chemical Composition and Mechanical Properties

COMPOSITION WEIGHT %						
C	Si	Mn	S	P	Ni	Cr	Mo
0.37	0.22	0.54	0.04	0.03	1.77	1.07	0.24

MECHANICAL PROPERTIES					
Orientation	.2% Proof Stress MPa.	UTS MPa.	Elongation %	R of A %	K_C MPa.$m^{\frac{1}{2}}$
A	1213	1307	13	39	95
B	1180	1285	7.8	26	47