EFFECTS OF STRENGTH AND GRAIN SIZE ON NEAR-THRESHOLD FATIGUE CRACK GROWTH IN ULTRA-HIGH STRENGTH STEEL

Robert O. Ritchie*

INTRODUCTION

Although much research in recent years has focused on fatigue crack propagation in metals, the slow growth of fatigue cracks at rates less than $10^{-5}$-$10^{-6}$ mm/cycle has received comparatively little attention. This is unfortunate since the majority of the lifetime of a cracked component would be spent in this region. Furthermore, a knowledge of a threshold stress below which fatigue cracks cannot propagate would be essential in the design of components which are subject to extreme high frequency, low amplitude loading for lifetimes of $10^{12}$-$10^{14}$ cycles [1].

The fatigue crack growth rate, $da/dN$, is generally related to the alternating stress intensity ($\Delta K = K_{\text{max}} - K_{\text{min}}$), developed at the crack tip, through a relationship [2] of the form

$$\frac{da}{dN} = C \Delta K^m,$$

where $C$ and $m$ are constants. Although this expression adequately described behaviour for the mid-range of growth rates ($\approx 10^{-5}$-$10^{-3}$ mm/cycle), it often underestimates the propagation rate at higher growth rates, where $K_{\text{max}}$ approaches $K_{\text{IC}}$, the fracture toughness, and is conservative at low growth rates ($< 10^{-5}$ mm/cycle) where $\Delta K$ approaches a threshold stress intensity, $\Delta K_0$, below which crack growth cannot be detected.

For the mid-range of growth rates fatigue crack propagation has been shown to be largely insensitive to such variables as mean stress, microstructure and test-piece thickness [3-5], and this is consistent with a ductile striation mechanism [6] of growth. At higher stress intensities the predominance of additional superimposed fracture mechanisms on striation growth ('static modes') results in an increasing sensitivity to mean stress, microstructure and thickness [3-5].

At very low stress intensities, which approach $\Delta K_0$, fatigue crack propagation again becomes dependent on mean stress and microstructure, although the precise fracture mechanisms are not well understood. It is clear, however, that the influence of environment is of paramount importance here. Previous studies in steels, aluminum and titanium alloys [eg. 7-10] have shown that $\Delta K_0$ is decreased and near-threshold crack propagation rates are increased at high stress ratios $R = K_{\text{min}}/K_{\text{max}}$. This $R$ dependence, however, can be severely reduced for tests in vacuum [7]. Mechanisms of growth in this region have been observed to be microstructurally sensitive involving the occurrence of environmentally induced fracture modes, such as intergranular fracture in steels. However, exactly which microstructures are beneficial in improving resistance to near-threshold fatigue failure is

* Department of Mechanical Engineering, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139, U. S. A.
The largest effect of microstructure was seen at low growth rates, where, for example, at $\Delta K = 9$ MPa$\sqrt{m}$, there was a factor of 100 times difference in growth rate between 100 and 650°C tempered conditions. As the tempering temperature was raised, the threshold $\Delta K^*$ increased from 3.0 to 8.5 MPa$\sqrt{m}$, concurrent with a two-fold reduction in tensile strength. Figure 2 shows this variation of $\Delta K^*$ at $R = 0.05$ and 0.7, with tensile strength, the inverse dependence of $\Delta K^*$ on strength being far less marked at the high $R$ ratio. Examination of the literature confirms this trend of increasing threshold and decreasing near-threshold growth rates with decreasing strength in steels (Figure 3). The effect is not seen at higher growth rates. Little variation in fracture mechanism was observed at low growth rates. All structures failed by a flat, fine-scale ductile transgranular mode containing segments of intergranular fracture. Intergranular facets were not seen in the 650°C tempered condition.

To assess the influence of grain size, specimens were austenitized at 870°C and at 1200°C, oil quenched and tempered at 300°C. The higher austenitizing temperature results in a larger prior austenite grain size (160 µm), yet the yield and ultimate strengths remain largely unaffected (i.e., Hall-Petch relationship does not apply). The mechanical properties are listed in Table 1. The fatigue results at $R = 0.05$ (Figure 4) indicate that, at low stress intensities, near-threshold crack propagation rates were lower in the larger grained structure although the value of $\Delta K^*$ was unchanged. This difference in crack growth rate was not observed at higher stress intensities. Fracture surfaces were much rougher in the coarse grained structure, showing a faceted, ductile, transgranular mode with segments of intergranular fracture.

DISCUSSION

It is clear that, for fatigue crack propagation in air at low stress intensities in high strength steels, decreasing the strength of the steel leads to a marked increase in threshold $\Delta K^*$ and a reduction in near-threshold crack propagation rates. Coarsening grain size also leads to lower near-threshold crack growth rates although the threshold itself remains unchanged. Thus, the proposed interrelation [11] between $\Delta K^*$, strength and grain size based on a Hall-Petch relationship does not apply in these ultra-high strength steels.

It is not clear why threshold $\Delta K^*$ and near-threshold crack propagation rates show a large dependence on strength. It is felt that one or more of the following reasons may apply: (1) If the growth of a fatigue crack near $\Delta K^*$ relies on some critical fracture stresses being exceeded near the crack tip, then, at some characteristic distance ahead of the crack tip, higher tensile stresses will be achieved in higher strength materials. The effect is enhanced in quenched and tempered steels by the greater work hardening capacity of structures tempered at lower temperatures. (2) In lower strength materials larger plastic zones are ahead of the crack tip, and hence residual stresses, arising from a crack closure effect [15], may be more effective in retarding crack growth. However, electrical potential measurements were unable to detect any crack closure, except below $K_{min}$, supporting previous observations [14] of negligible closure for crack growth under plane strain conditions. (3) The effect is more likely to arise from the increased susceptibility of higher strength steels to environmental influences of hydrogen in moist air. Increased strength can result in a higher equilibrium solubility of hydrogen in the crack tip region (due to higher triaxiality), and a reduction of hydrogen.
necessary to cause cracking [15]. This is reflected in the reduction in $\Delta K_{\text{eq}}$, the threshold for hydrogen and stress corrosion cracking in steels, with increased strength. It is conceivable that the same effect influences near-threshold fatigue crack propagation rates in humid air.

The superior near-threshold fatigue crack propagation rates observed in coarse grained structures are, similarly, thought to be environmentally induced, since little grain size dependence is seen at higher growth rates. The environmental influence of hydrogen is greatest when the maximum plastic zone is of the order of the grain size [7], such that hydrogen atoms can be swept-in by dislocations into grain boundaries. In coarser grained structures the plastic zone remains small compared to the grain size until much higher stress intensities (in present study $\Delta K \approx 30$ and 90 MPa m$^{-1/2}$ in 870°C and 1200°C austenitized structures respectively when maximum plastic zone equals grain size), resulting in a reduced environmental influence. Experiments are now being performed in dry, inert argon atmospheres in an attempt to clarify the above effects.

The environmental influence of hydrogen from moist air can be enhanced, however, by varying the cooling rate after tempering. In 300-M steel, slow step-cooling (instead of oil quenching) after tempering at 650°C, to allow segregation of impurity elements to prior austenite grain boundaries, results in increased near-threshold fatigue crack propagation rates, and a reduction in the threshold $\Delta K_0$ from 8.5 to 6.2 MPa m$^{-1/2}$ [16]. Here the grain boundaries are embrittled by impurity segregation, and are consequently more susceptible to intergranular hydrogen-assisted cracking during slow fatigue crack growth.

In summary, it is apparent that microstructure has a large influence on fatigue crack propagation behaviour at low stress intensities. Improved resistance to near-threshold fatigue crack growth in steels can be achieved through lower strength and coarser grained structures, although whether these effects are mechanically or environmentally induced remains an open question.

ACKNOWLEDGEMENTS

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REFERENCES


Table 1 Mechanical Properties of 300-M Steel

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<th>Austenitizing Temp. (°C)</th>
<th>Tempering Temp. (°C)</th>
<th>Prior Austenite Grain Size (μm)</th>
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<th>T.S. (%)</th>
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Table 1 Mechanical Properties of 300-M Steel

*Estimated from equivalent energy at maximum load.
Figure 1 Variation of Fatigue Crack Growth Rate (da/dN) with Alternating Stress Intensity (ΔK) at R = 0.05, for 300-M Steel, Quenched and Tempered Between 100°C and 650°C, Showing Influence of Material Strength

Figure 2 Influence of Ultimate Tensile Strength on Threshold for Fatigue Crack Growth (ΔK_0) in 300-M Steel, Tested in Air

Figure 3 Summary of Results Showing Variation of Threshold (ΔK_0) at R = 0 with Yield Strength for Steels

Figure 4 Variation of Fatigue Crack Growth Rate (da/dN) with Alternating Stress Intensity (ΔK) for 300-M Steel, Austenitized at 870°C and 1200°C, Showing Influence of Grain Size