Microstructural Effects and Crack Closure during Near
Threshold Fatigue Crack Propagation in a High Strength Steel

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Near threshold fatigue crack growth behavior of a high strength steel under different tempered conditions was investigated. The important aspect of the study is to compare the crack growth behavior in terms of the closure-free component of the threshold stress intensity range, $\Delta K_{th,off}$. While a systematic variation in the absolute threshold stress intensity range with yield strength was observed, the trend in the intrinsic $\Delta K_a$ or $\Delta K_{th,eff}$ exhibited a contrasting behavior. This has been explained as due to the difference in fracture modes during near threshold crack growth at different temper levels. It is shown that in a high strength and high strain hardening microstructure, yielding along crystallographic slip planes is difficult and hence it exhibited a flat transgranular fracture. In a steel with low strain hardening characteristics and relatively low strength, a tendency to intergranular planar slip is observed consequently resulting in high $\Delta K_a$. Occurrence of a predominantly intergranular fracture is shown to reduce intrinsic $\Delta K_a$ drastically and increase crack growth rates. Also shown is that crack closure can occur in high strength steels under certain fracture morphologies. A ‘transgranular planar slip’ during the inception of a ‘microstructure sensitive’ crack growth is essential to promote intergranular and faceted fracture. The occurrence of a maximum in the fraction of intergranular fracture during threshold crack growth corresponds to the $\Delta K$ value at which the cyclic plastic zone size becomes equal to the prior austenitic grain size.

I. INTRODUCTION

Materials exhibit progressive crack growth under cyclic loading conditions in service, often called ‘subcritical crack growth’, until a crack size corresponding to the critical size is reached where the failure occurs catastrophically. Hence optimization of design of engineering structures and components for fatigue and fracture resistance requires a knowledge of the fatigue crack growth behavior and fracture toughness under a variety of microstructural conditions. A large amount of crack growth data under cyclic loading, with crack growth rates larger than $10^{-4}$ mm/cycle, on a wide range of materials and microstructures, has been generated in recent years which seem to obey ‘Paris’ Law’. Crack growth rates lower than this are found to be affected by microstructure, and several studies have emerged showing the reduction in crack growth rates at low $\Delta K$ levels by modifying the micromechanics of fracture at the crack tip through a microstructural change. In this respect, local variations in microstructure such as grain size, retained austenite, and temper embrittled structure have been found to affect the near threshold crack growth rates significantly apart from other mechanical variables like load ratio and environment. Most of these observations can often be explained by crack closure and environment induced embrittlement effects. In low strength steels, a comparison of ferritic, ferrite-pearlitic, isothermally transformed bainitic, and martensitic structure for threshold fatigue crack propagation resistance had been made, and it was shown that ferritic and ferrite-pearlitic microstructures have high thresholds for crack growth. Obviously, the crack growth mechanisms and the associated crack tip plasticity levels are different in these microstructures, and in ferrite the greater extent of plastic deformation and crack closure was responsible for high threshold level. While the mechanism by which the crack growth behavior is affected is clear in low strength steels to some extent, there exists considerable difficulty in understanding the mechanisms behind crack growth in quenched and tempered high strength steels. Some studies have reported the effect of tempering temperature on $\Delta K_a$ in high strength steels, and it was demonstrated that increasing the tempering temperature, $\Delta K_a$ value increased and crack growth rates decreased and it was attributed to be merely a dependence on yield strength. The present investigation is an attempt on similar lines to study the effect of tempered structure on $\Delta K_a$ in a high strength steel. However, the prime objective was to compare the crack growth behavior through the intrinsic material threshold and crack closure. The intrinsic threshold is defined as the closure-free component of the threshold and is expressed as:

$$\Delta K_{th,off} \quad \text{or} \quad \Delta K_{th,inear} = K_{max,th} - K_{closure,th} \quad [1]$$

where $K_{max,th}$ and $K_{closure,th}$ are the maximum and crack opening stress intensity levels in a fatigue cycle at threshold. One would expect that in microstructures, depending on yield strength and strain hardening behavior, the response of the material to crack tip deformation would be essentially different. By varying the tempering temperature, not only the mechanical properties are altered, but also changes in the chemistry of specific regions in the microstructure are brought about; e.g. grain boundary embrittlement when tempered in the range 350 to 500 °C. Since the crack velocity during near threshold crack growth is strongly influenced by fracture parameters ahead of the crack tip, this would be expected to give rise to severe alterations in crack growth conditions. As will be shown, the intrinsic value of the...
threshold stress intensity range and the magnitude of crack closure near threshold are predominantly affected by crack tip fracture modes.

II. EXPERIMENTAL PROCEDURE

The steel used in the present investigation conformed to the following composition: C 0.32, Si 1.2, Cr 1.0, Mn 1.0, and Ti 0.2 pct. Air induction melted steel billets were hot forged and normalized. Compact tension samples of 6.5 mm thickness conforming to ASTM 647-81 fatigue crack growth test standard were machined from forge stock with the orientation of the notch in the long transverse direction. Specimens were austenitized at 1100 °C for 30 minutes in a neutral salt bath furnace followed by oil quenching. Tempering was carried out at 300, 400, and 530 °C for 135, 35, and 25 minutes, respectively, and then water quenched. The prior austenitic grain size in the quenched and tempered condition was 6.5 μm.

Fatigue crack growth tests were performed in a servohydraulic machine at a frequency of 35 Hz in the laboratory environment of 50 to 60 pct relative humidity and at room temperature (20 °C). Tests were conducted maintaining a load ratio of 0.05 in order to study the crack closure effects. A conventional load shedding technique was employed for approaching threshold condition. The cracks were initiated at a high ΔK with corresponding crack growth rates being approximately 10⁻³ mm/cycle, and subsequently the load was reduced by less than 10 pct at each step while the crack growth rates were measured. At each load level the crack was allowed to propagate for at least 0.1 mm with crack tip position measurements made after the crack tip passed a distance corresponding to several times the sizes of maximum plastic zone formed at the previous load level. Crack growth was monitored using both optical and AC potential drop methods. The resolution of crack length measurements was better than 0.1 mm. The threshold stress intensity range was experimentally defined as the ΔK level at which a crack growth rate of 10⁻⁷ mm/cycle was reached.

Crack closure measurements were performed using a COD gage. At each load step the load vs crack mouth opening displacement were plotted using an X-Y recorder at a reduced test frequency of 0.02 Hz. Both the loading and unloading compliance curves were recorded, and the closure load was determined as the average of the load level at which a change in slope occurs in both the compliance curves.

Scanning electron microscopy was used to assess the fracture topography at each ΔK level and its relation to crack growth at the various stages of the crack growth curve. A quantitative estimation of the fracture surface was performed by taking fractographs continuously from the crack tip. The area fraction of intergranular fracture was estimated using a transparent graph sheet and counting the fraction of squares occupied by intergranular fracture.

III. RESULTS

Optical micrographs of the samples tempered at 300, 400, and 530 °C are given in Figures 1(a), (b), and (c). The microstructures show typical tempered martensite obtained after quenching and tempering. Mechanical properties of the microstructures after different tempering treatments are given in Table I.

In general a reduction in yield strength and ultimate strength can be noted with increase in tempering temperature with a small increase in percentage elongation and fracture strain. However, as seen in Table I, the monotonic strain hardening exponent shows considerable variation, and hence it appears that this controls the strength levels in this steel.

Crack growth curves for the tempering treatments investigated are given in Figures 2 through 4. In Figures 2 and