Near Threshold Fatigue Crack Growth Behaviour of a High Strength Steel: The Effect of Prior Austenitic Grain Size

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Near threshold fatigue crack propagation behaviour of a high strength steel under different prior austenitic grain sizes with constant tensile properties was investigated. Attention has been paid to the observation of facture modes at threshold in different grain sizes. The observations indicate that three distinct modes of fracture can occur at threshold depending on the resistance offered by the grain boundary to the plastic relaxation of crack tip stress state by transgranular crystallographic slip. A low value of threshold was encountered in fine grain sizes due to limited slip distance where as higher thresholds were seen in coarse grain sizes where dislocation pile-up and extensive plastic relaxation at the crack tip can occur to give rise to crack path tortuosity and crack blunting respectively.

Ermüdungsrißwachstum eines hochfesten Stahls nahe dem Schwellwert: Der Einfluß der vorhergehenden Austenitkorngröße

Das Wachstumsverhalten von Ermüdungsrissen eines hochfesten Stahl mit verschiedenen vorausgehenden Austenitkorngrößen aber konstanten Zugeigenschaften wurde nahe dem Schwellwert untersucht. Besondere Aufmerksamkeit wurde den Bruchmoden beim Schwellwert bei verschiedenen Korngrößen gewidmet. Es zeigte sich, daß drei Bruchmoden unterschieden werden können, je nach dem Widerstand der Korngrenze gegen plastische Relaxation der Rißspitzenspannung durch transgranulares Gleiten. Ein niederer Schwellwert wird bei feiner Korngröße wegen der begrenzten Gleitabstände gefunden, während höhere Grenzwerte in grobem Korn zu sehen sind, wo Versetzungsaufstau und ausgeprägte plastische Relaxation an der Rißspitze auftreten, die zu einer Rißumlenkung und zu Rißverzweigung führen.

1 Introduction

Near threshold fatigue crack growth behaviour of engineering metals and alloys has received considerable attention in literature, owing to wide spread use of a defect tolerant design approach[1)2)3)]. Such a growth behaviour is characterised by crack velocities lower than 10^{-6} mm/cycle typically and the crack growth has been termed "microstructurally" sensitive[3)]. Among several variables, like load ratio, environment, temperature, grain size and microstructure, grain size has been found to significantly influence the crack growth rates. Investigations relating to the effect of grain size in steels[1)2)], Ni-base alloys[4)] and titanium alloys[5)] are well documented. While the influence of grain size on threshold fatigue crack growth behaviour in low strength steels has been reported by several investigators, similar studies aimed at understanding the effect of prior austenitic grain size in quenched and tempered martensitic high strength steels are inadequate[1)2)6)7)8)] and often are lacking in clarity. These studies were restricted to grain sizes generally of the order of 20 μm and above, where the sizes of the crack-tip plastic zone were always lower than the grain sizes investigated. A genuine effect of grain size on the near threshold fatigue crack growth behaviour can be understood only if the microstructures, composition and heat treatment of the steel were optimised to achieve a plastic zone size at threshold comparable to the prior austenitic grain size. Moreover, in these investigations fractographic evidences which greatly assist in formulating a micro-mechanistic explanation of the observed trends, are lacking. The present investigation is aimed at explaining the pattern in which the prior austenitic grain size influences the crack growth behaviour near threshold based on microfracture processes and crack closure mechanisms operating at threshold in a high strength steel. For this purpose, a medium carbon high strength steel alloyed with titanium is chosen in order to obtain very fine grain sizes. It is possible to obtain extremely fine grain sizes (0.7 μm) in this steel by conventional austenitizing treatments. The observed dependence of fatigue crack growth threshold parameter, ΔK_{th} on the prior austenitic grain size has been explained on the basis of the consideration that the deformation is localised along crystallographic slip planes when the crack tip plasticity levels are comparable or lower than the prior austenitic grain size.

2 Experimental Procedure

The steel used in the present investigation analysing: C 0.32, Si 1.2, Mn 1.0, Cr 0.98, Ti 0.2, S 0.015 and P 0.02 % was austenitized at 900, 1000, 1100, 1200 and 1250 °C for 30 min, oil quenched and tempered at 530 °C for 25 min. Fatigue crack growth testing was performed on 6.5 mm thick compact tension specimens with $R = 0.05$ in a 100 KN servohydraulic Instron testing machine. Tests were conducted at room temperature in laboratory air with 50 to 60 % relative humidity and at a frequency of 35 Hz. A conventional load shedding procedure was employed and crack lengths were measured using both optical and alternating current potential drop (ACPD) techniques. A cyclic stress intensity range corresponding to a crack growth rate of 10^{-3} mm/cycle was initially applied and the load was reduced at each level by less than 10 %. At each load level, the crack was allowed to propagate several times the size of the monotonic plastic zone formed at the previous load level after which the crack growth rates were measured. The resolution of crack length measurements was better than 0.1 mm. The threshold stress intensity range, ΔK_{th} in this study, is defined as the one at which a minimum crack growth rate of the order 10^{-7} mm/cycle was reached. Crack closure measurements were performed using crack opening displacement (COD) gauge mounted on the mouth of the crack. The crack opening stress intensity level, K_{op} is defined as the stress intensity level at which a change in slope was observed in the load-versus displacement record made at each load level.

Table 1. Mechanical property data as a function of heat treatments employed for the steel.

Aust/ Temper (°C)	0.2 % YS (MPa)	UTS (MPa)	Eln (%)	ε_f [a]	η [b]	GS [c] (μm)	CPZS [d] (μm)	MPZS [e] (μm)
900/530	1108	1168	13	0.74	0.15	0.7	0.14	0.6
1000/530	1122	1173	14	0.80	0.12	3.0	0.20	0.8
1100/530	1096	1164	12	0.80	0.19	6.5	1.5	6.0
1200/530	1038	1160	12	0.63	0.24	16.5	1.2	5.0
1250/530	1087	1179	12	0.66	0.12	96.0	2.0	8.0

[a]) Fracture strain, $\varepsilon_f = \ln(1/(1 - RA))$
[b]) Strain hardening exponent
[c]) Prior austenitic grain size
[d]) Cyclic plastic zone size = $(1/3\ \pi)\ (\Delta K/2\ \sigma_{ys})^2$
[e]) Monotonic plastic zone size = $(1/3\ \pi)\ (K_{max}/\sigma_{ys})^2$

3 Results

The mechanical properties and grain sizes of the steel after different austenitizing treatments are given in Table 1. Austenitizing at 900 °C produced an extremely fine grain size (0.7 μm) while austenitizing at 1250 °C resulted in coarsening of the grain size to 96 μm. The very fine grain size in this steel is achieved because of the presence of titanium carbides and carbonitrides. It can be seen from Table 1 that the values of yield strength after different austenitization treatments are almost the same, characteristic of high strength steels. Also the fracture ductility measured as fracture strain and the strain hardening behaviour are independent of the grain size. The low strain hardening behaviour of these microstructures would result in deformation conditions at the crack tip close to that of an ideally plastic material.

Fatigue crack growth curves for the different grain sizes investigated are presented in Figs. 1 and 2 in the form of log (da/dN) vs log (ΔK) and log (ΔK_{eff}) respectively.

ΔK_{eff} is computed from:

$$\Delta K_{eff} = K_{max} - K_{min} \text{ for } K_{op} < K_{min} \quad (1)$$

$$\Delta K_{eff} = K_{max} - K_{op} \text{ for } K_{op} > K_{min} \quad (2)$$

where K_{max}, K_{min} and K_{op} are respectively the maximum, minimum and crack opening stress intensity levels in the fatigue loading cycle. Figure 3 shows the variation in ΔK_{th} with increase in prior austenitic grain size of the steel investigated. Scanning electron fractographs representative of fracture features observed at threshold are represented in Figs. 4 to 7. Macrographs of the fracture surfaces are shown in Fig. 8. A schematic illustration of the crack tip events that might occur to give rise to the differences in ΔK_{th} and crack closure is shown in Fig. 9 based on the fractographic observations.

4 Discussion

The effect of grain size on the crack growth behaviour near threshold has been reported in several studies[3)4)5)9) to 14)] on different alloy systems and in general, an increase in the fatigue crack growth resistance was observed with an increase in grain size. This is attributed to the increased crack path deviation during crystallographic crack growth resulting in crack tortuosity[11)], an increase in effective crack length[9)], roughness induced crack closure[14)] and localised crack tip retardation[12)13)] at grain boundaries when the crack tip plasticity is confined within a grain. These observations had been made at low crack growth rates at which the crack tip tends to follow crystallographic planes resulting in slip localisation ahead of the crack tip[12)13)] and causing a slip band decohesion[11) to 13)] and a mixed mode of fracture[11)12)] involving transgranular crystallographic and intergranular facets. In low strength steels, with ferritic and pearlitic microstructures, an increase in ΔK_{th} with grain size was observed[9)10)14)] and was interpreted to be due to a reduction in yield strength as well as a crystallographic crack growth mode[10)] in coarse grained structures.

It is worthwhile to briefly review the reported results on the effect of prior austenitic grain size on ΔK_{th} in high strength steels. A reduction in ΔK_{th} was observed when the prior

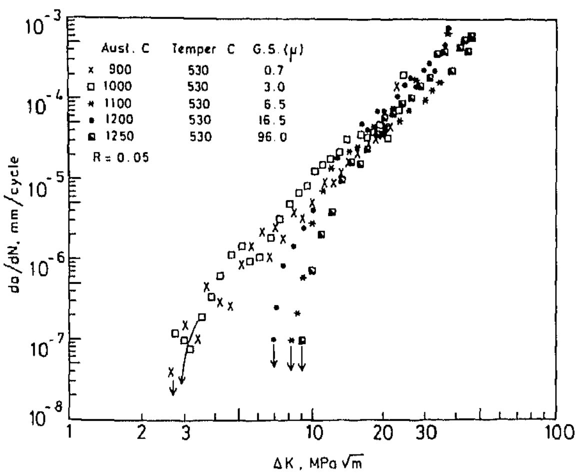


Fig. 1. da/dN vs. ΔK plot for the grain sizes investigated.

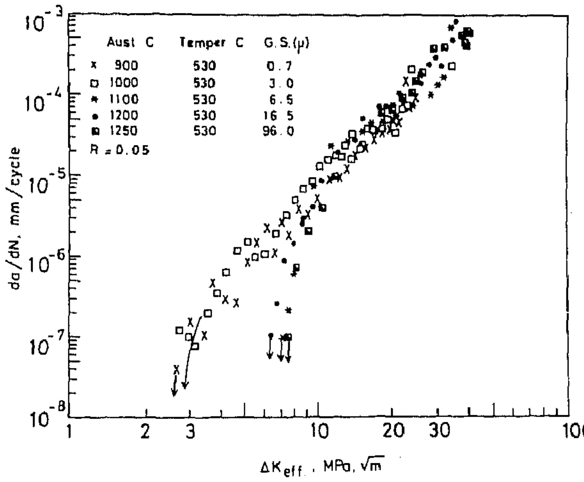


Fig. 2. da/dN vs. ΔK_{eff} plot for the grain sizes investigated.

austenitic grain size was increased in Fe-Cr-C steel[6]. Whereas in a quenched and tempered AISI 4340 steel[7], apparently no sensitivity of ΔK_{th} to the variations in the prior austenitic grain size was noted. Since the sizes of plastic zones at the crack tip were low relative to that of prior austenitic grains in these studies, it would be difficult to interpret the variations in the ΔK_{th} based on the prior austenitic grain size. A strong dependence of ΔK_{th} on prior austenitic grain size has been observed[15] for a 12CrNi3A steel. Murakami et al.[8] demonstrated that both increasing and decreasing trends in ΔK_{th} with an increase in the prior austenitic grain size were observable. Recently, in a high carbon high chromium steel[16], an increase in ΔK_{th} with the prior austenitic grain size was encountered and it was attributed to the increase in the level of plastic flow and crack closure caused by retained austenite. However, in most of these investigations, fractographic evidences to support the micromechanistic processes explained seem to be inadequate.

In the present investigation, some interesting aspects on the dependence of ΔK_{th} on the prior austenitic grain size observed have been reported. An attempt has been made to explain the results on the basis of the size of the plastic zone at the crack tip relative to the grain size. In Fig. 3, there is seen a rapid increase in ΔK_{th} from fine grain size (ΔK_{th} = 2.6 MPa$\sqrt{m}$; GS = 0.7 μm) to intermediate grain size (ΔK_{th} = 7 MPa$\sqrt{m}$; GS = 16.5 μm) after which the increase in ΔK_{th} is small at large grain sizes. A close comparison between Figs. 1 and 2 suggests that although crack closure cannot completely be responsible for the observed effects, indeed differences in ΔK and ΔK_{eff} and the crack growth rates of 6.5, 16.5 and 96 μm grain size structures can be noted. The difference between the crack growth rates tend to be smaller when plotted against ΔK_{eff} (Fig. 2). Previous work[1,2] on the effect of prior austenitic grain size in ΔK_{th} suggested an environment-induced intergranular fracture mechanism for the acceleration in crack growth which does not agree with the observations of transgranular fracture in earlier investigations[1,2,6] as well as in the present study. An examination of the fracture morphology at threshold in different grain sizes presented in Fig. 4 to 7 suggest that three distinct fracture mechanisms operated during near threshold fatigue crack growth; a flat transgranular fracture, crystallographic crack growth and a ductile mode of crack growth in fine, intermediate and coarse grains sizes respectively. Figures 4a and b show a flat transgranular quasi-cleavage fracture at threshold in the fine grain size (0.7 μm) material. On the other hand, intermediate grain sizes (6.5 and 16.5 μm) exhibited crystallographic crack growth along slip planes leading to the development of transgranular facets on the fracture surface (Figs. 5 and 6). In Figs. 5a and b shown is the crystallographic fracture morphology occuring close to threshold. The occurance of crystallographic faceted fracture morphology can be attributed[17,18] to the planar slip mode as a result of the low strain hardening behaviour of these microstructures. The presence of oxide debris (indicated as "D") on the fracture surface together with crystallographic facets (indicated as "C") is seen in Fig. 5a. At very large grain size (96 μm), the fractographs presented in Figs. 7a and b show features indicative of extensive plastic deformation during crack growth. Macrographs of the fracture surfaces of the samples tested for fatigue crack growth are presented in Fig. 8. The threshold region is indicated by the arrows. It can be seen that in coarse grained samples (6.5, 16.5, and 96 μm), oxide debris on the fracture surface is present and evidently is maximum in 6.5 μm grain size sample compared to the other samples. The absence of any oxide debris on the fracture surface of the sample with 0.7 μm grain size can also be noted.

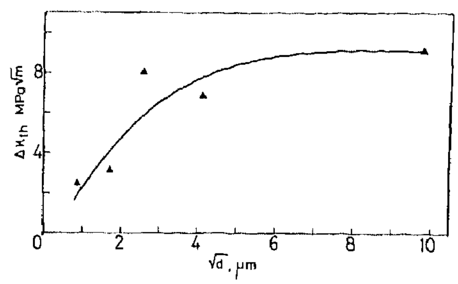
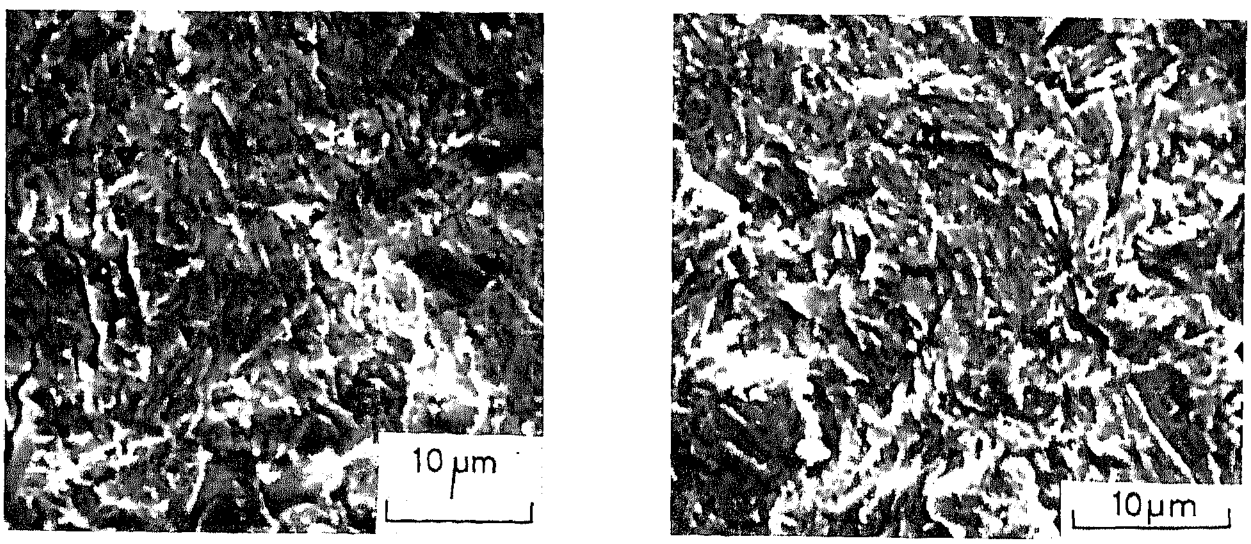
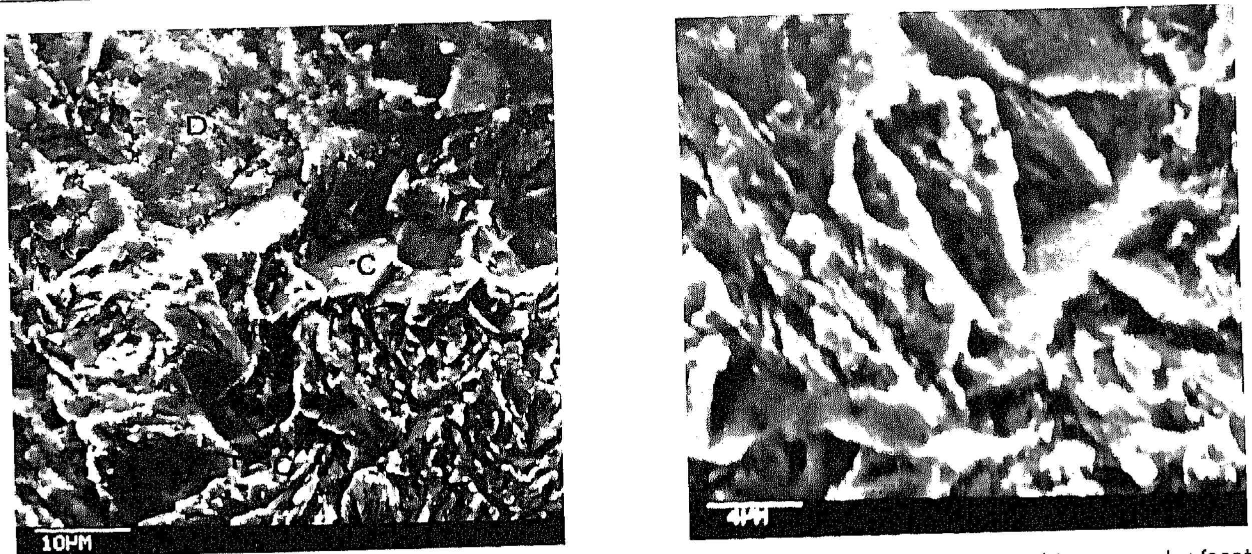


Fig. 3. Variation of ΔK_{th} with prior austenitic grain size.

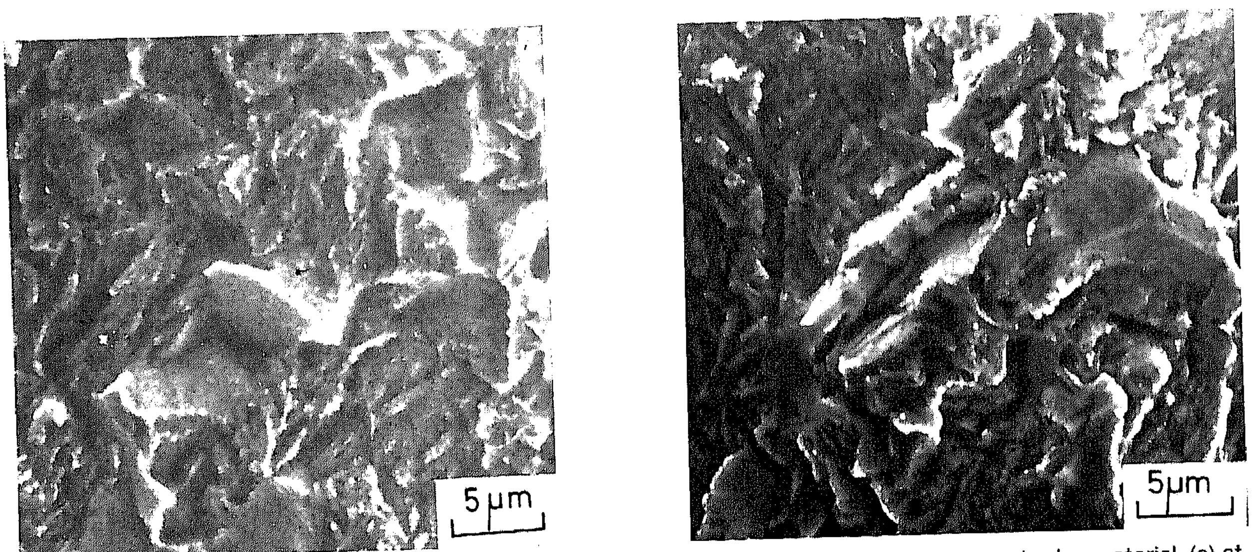
It is of interest to examine the slip behaviour at the crack tip on the basis of which these different modes of fracture could be explained meaningfully. It is to be noted that all the tensile properties, viz., yield and ultimate strength, fracture strain and strain hardening exponent for these grain sizes are closely the same. The morphological changes in titanium carbides/carbonitrides during various



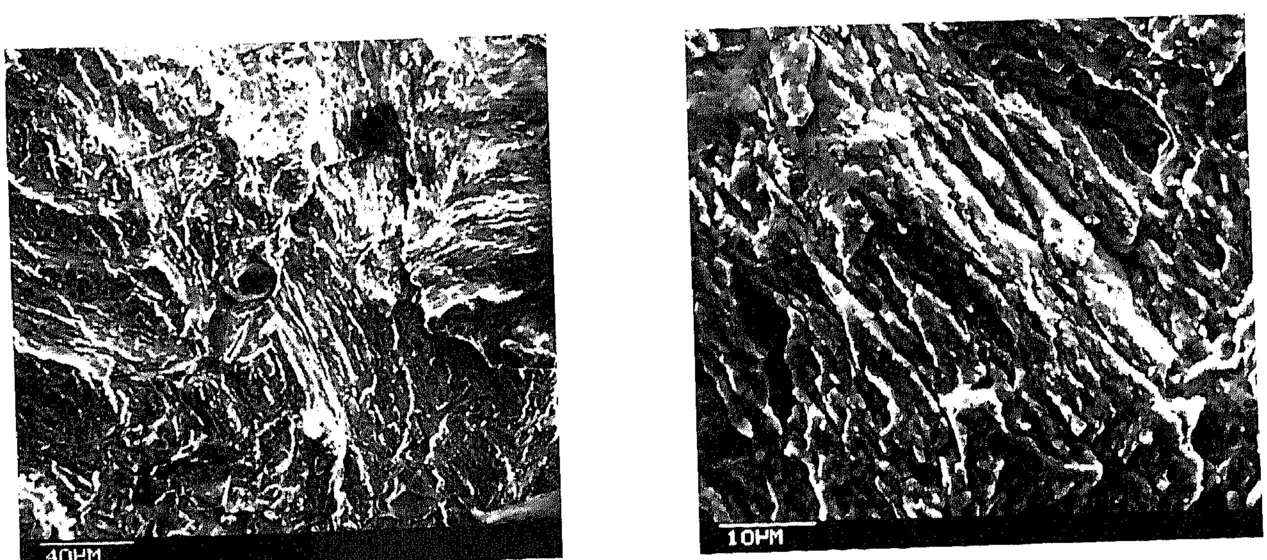
Figs. 4a and b. Fractographs showing a flat transgranular fracture path for 0.7 μm grain size material, (a) at ΔK_{th} and (b) at a slightly high ΔK level.



Figs. 5a and b. Fractographs showing a crystallographic mode of crack advance exhibiting slip induced transgranular facets for 6.5 μm grain size material, (a) at $\Delta K = 11$ MPa$\sqrt{m}$ and (b) at $\Delta K = 13$ MPa$\sqrt{m}$. The presence of oxide debris (marked "D") together with crystallographic facets (marked "C") can be noted.



Figs. 6a and b. Fractographs illustrating a faceted mode of crack growth near threshold for 16.5 μm grain size material, (a) at ΔK_{th} and (b) at a slightly high ΔK level.



Figs. 7a and b. Fractographs showing fracture at threshold involving extensive plastic deformation marked by ripple-like ductile markings at threshold for 96 μm grain size material, (a) at ΔK_{th} and (b) same as (a), but at a high magnification indicating slip band cracking (secondary cracking).

austenitizing treatments could possibly influence the crack growth behaviour near threshold. However, extensive scanning electron microscopic investigations[19] failed to detect any evidence for carbide induced cleavage or void nucleation at threshold and hence it is presumed that carbides bear no significance with respect to crack growth behaviour in this steel. In a recent study[20], it was shown that titanium carbides/carbonitrides do not affect fatigue crack growth. Hence, the observed differences in ΔK_{th} values could only be due to the variations in the prior austenitic grain size.

Near the threshold, the crack tends to propagate along crystallographic planes in which slip is easier[11] to [13] and hence the crack growth rates are controlled by slip plane orientations. When deformation is localised along crystallographic planes ahead of the crack tip under plane strain conditions[21] to [23], the grain boundary ahead of the crack can offer resistance to slip causing a dislocation pile-up. This can result in a retardation in crack growth. Hence, one would expect that finer the grain size, lower the degree of slip and plastic relaxation because of a limited pile-up distance and the back stress associated with already piled-up dislocations. As a result of high triaxiality, a flat transgranular quasicleavage fracture could occur as shown in Figs. 4a and b for a grain size of 0.7 μm. At intermediate grain size (6.5 μm), slip could be accomodated along crystallographic planes until the stress due to dislocation pile-up causes decohesion along these planes. An environmental contribution through H_2 in moist laboratory air could favour such a stage I cracking process[24] in fatigue. This produces a facet, inclined at certain angles to the fracture plane causing crack path tortuosity and crack closure (Figs. 5a and b). Besides, as seen in Table 1, the crack tip maximum plastic zone size at threshold is equal to the grain size. At this stage, slip localisation and slip band decohesion[8][12][13][16][25] to [27] are effective processes in retarding crack growth, consistent with earlier observations of crack growth deceleration when the maximum plastic zone size[28] and the monotonic overload induced plastic zone size[29] were equal to grain size in aluminium alloys. Interestingly, Li Nian et al.[15] reported a variation in ΔK_{th} with prior austenitic grain size similar to the one noted in this study. Both slip band decohesion and faceted fracture morphology was suggested to be responsible for high ΔK_{th} values at intermediate grain sizes when the plastic zone size was equal to prior austenitic grain size at threshold. In the present study, the extent of fracture surface oxidation was also maximum at intermediate grain size (6.5 μm) as shown in Fig. 8. Such oxide debris formation at threshold is due to the strong crystallographic zig-zag crack growth and can increase ΔK_{th} by oxide induced crack closure[30]. Figures 6a and b illustrate similar faceted fracture at threshold for the grain size of 16.5 μm even though the computed plastic zone size is smaller than the grain size. However, the transgranular facets could also occur as a result of the influence of martensitic packet boundaries in this material. In the large grain size material (96 μm), the size of the plastic zone is smaller than the grain size. Hence, a high degree of slip can occur causing crack blunting due to a lack of constraint as well as the presence of retained austenite after high temperature austenitization[16]. Figures 7a and b indicate a ductile mode of crack advance for this material. At a high magnification, the fracture surface exhibits secondary cracking as a result of slip band cracking after extensive slip similar to previous observations[31][32]. The schematic illustrating the crack tip micro-fracture processes at various grain sizes is presented in Fig. 9.

It is to be noted that earlier investigations[1][6] showing an absence of strong variation in ΔK_{th} with prior austenitic grain sizes were generally performed with lightly tempered microstructures where the high strain hardening matrix could result in transgranular brittle fracture. However, a maximum in ΔK_{th} was observed[8][15] when the plastic zone was equal to grain size in highly tempered microstructures where a strong grain boundary effect can be realised due to planar slip. In a recent study[33] the authors have used the differences in slip behaviour in variously tempered structures to rationalise the observed disparity in the results reported in literature.

The present observations qualitatively agree with the report of the results on Fe-Ni-Al[12], Al and Ti alloys[13][28]. The effect of crack deflection and secondary cracking during crystallographic crack growth on the slope of the fatigue crack growth curve can be readily understood with reference to Fig. 10. Results in this investigation agree well with this type of qualitative description of crack growth behaviour at threshold.

5 Conclusions

From the present study, it can be concluded that near threshold fatigue crack growth rates decrease and ΔK_{th} increases with an increase in the prior austenitic grain size.

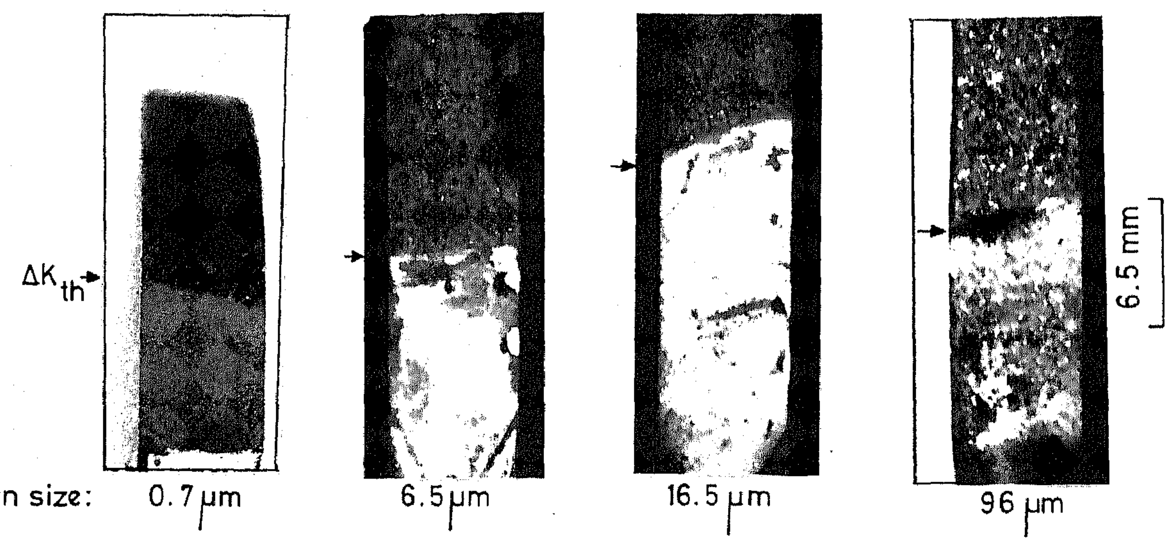


Fig. 8. Macrographs of the fracture surfaces.

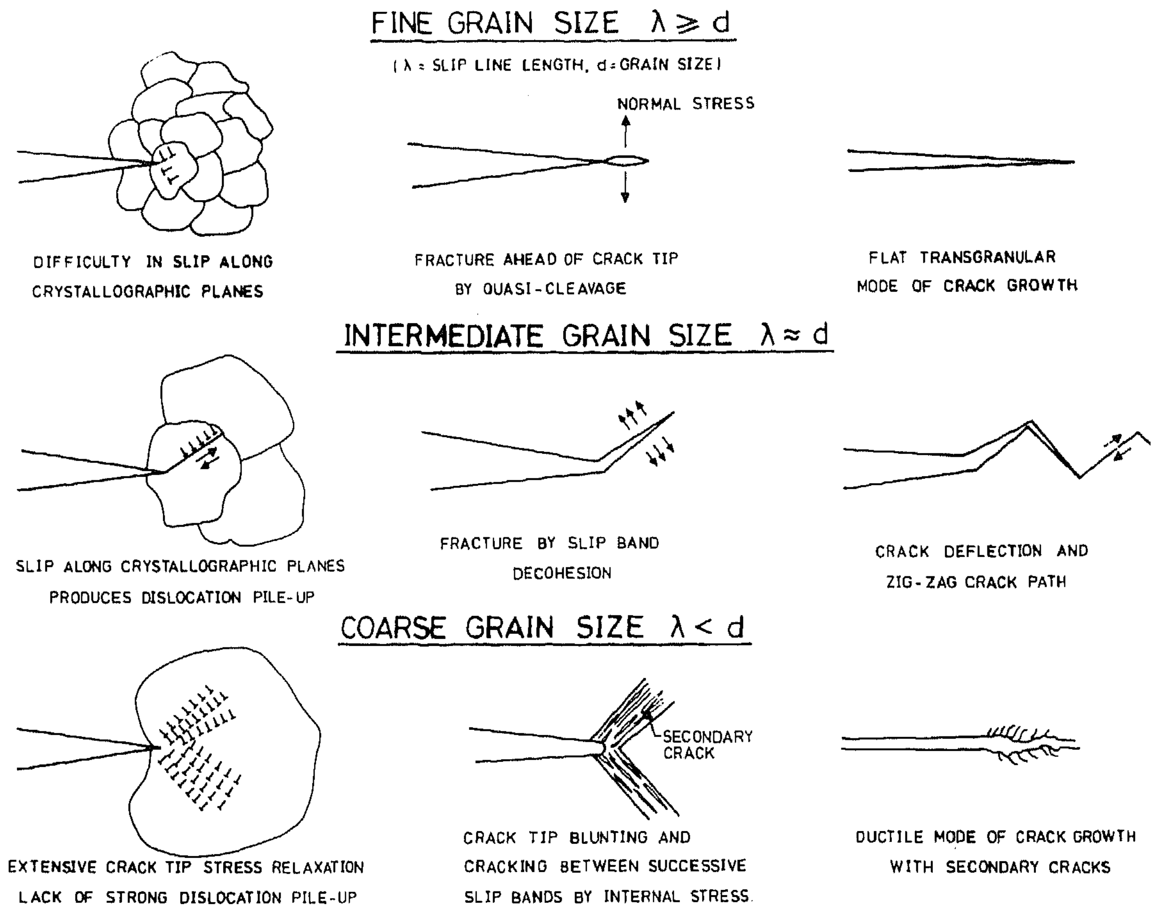


Fig. 9. Schematic illustration of crack tip-grain boundary interactions and microfracture processes.

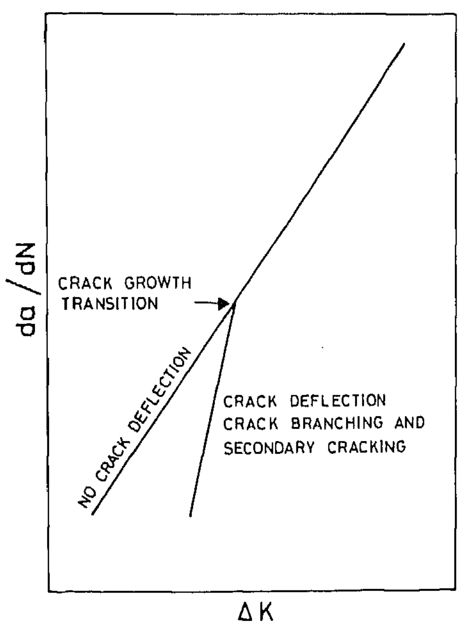


Fig. 10. Schematic illustration of crack growth deceleration near threshold caused by crack deflection, crack branching and secondary cracking.

The manifestation of the effect of prior austenitic grain size on ΔK_{th} is by altering the mode by which the crack tip stresses are relaxed consequently giving rise to crack deflection, crack closure and crack blunting. At much finer grain sizes the grain boundary imposes difficulty to yield along slip planes because of limited slip distance. As a result of this a normal stress develops and a flat transgranular fracture occurs giving low ΔK_{th}. In intermediate grain sizes where the crack tip plasticity levels are comparable to grain size, the development of crystallographic facets leading to crack tortuosity and oxide induced crack closure increases ΔK_{th}. At much larger grain sizes crack tip blunting and secondary cracking due to extensive plastic relaxation around the crack cause the highest ΔK_{th}.

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