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M. F. Carlson and R. O. Ritchie

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ON THE EFFECT OF PRIOR AUSTENITE GRAIN SIZE ON NEAR-THRESHOLD FATIGUE CRACK GROWTH

by

M.F. Carlson* and R.O. Ritchie**

*Department of Materials Science and Mineral Engineering,
Materials and Molecular Research Division
Lawrence Berkeley Laboratory
University of California
Berkeley, California 94720

**Department of Mechanical Engineering,
Massachusetts Institute of Technology
Cambridge, Massachusetts 02139

INTRODUCTION

It is generally accepted that the fatigue or endurance strength of planar slip materials, such as steel and brass, is increased by refining the grain size, whereas in wavy slip materials, such as pure copper and pure aluminum, the fatigue strength is unaffected (1,2). However, there is little similar evidence of an effect of grain size on fatigue crack propagation (2). In both wavy (3,4) and planar slip (5-7) metals, growth rates appear independent of grain size. For example, variations in grain size from 10 to 200μm in 70/30 brass (6), and from 45 to 480μm in austenitic stainless steel (7) produce no measurable change in fatigue crack propagation rates over a range of growth rates from 10^{-5} to 10^{-2} mm/cycle.

Recently, however, there have been indications in the literature that grain size may indeed influence crack propagation behavior at growth rates less than 10^{-5} to 10^{-6} mm/cycle approaching the threshold* for crack propagation, ΔK_0 (8-13). Robinson and Beevers (8) report an order of magnitude decrease in near-threshold growth rates in α-titanium after coarsening the grain size from 20 to 200μm. Similar effects have been seen in Ti-6Al-4V (9). Furthermore, Masounave and Baïlon (10,11) have observed a marked increase in threshold ΔK_0 values in a range of low strength steels by increasing ferrite grain size. In all the above studies however, no attempt was made to control strength; and the effect of coarsening the grain size may well have been caused by a concurrent decrease in material strength, particularly since it is known that, in steels at least, near-threshold fatigue crack growth is markedly decreased by reducing the yield strength** (10-15). A comparison at constant yield strength between coarse and fine-grained materials has been made (13) in ultra-high strength steel (300-M) where it was found that, on enlarging the (prior austenite) grain size from 20 to 160μm, a small reduction in near-threshold propagation rates below 10^{-4} to 10^{-5} mm/cycle resulted with no change in the threshold ΔK_0. The object of the present note is to examine further the effect of prior austenite grain size on near-threshold fatigue crack growth behavior in a high strength steel (Fe-Cr-C) where grain size can be varied considerably without significant change in monotonic and cyclic strength.

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*The threshold ΔK_0 represents the alternating stress intensity below which crack growth cannot be detected.

**More correctly, the cyclic yield strength (13,15).

EXPERIMENTAL PROCEDURES

The material studied was an experimental, high toughness, high strength steel (Fe-Cr-C) containing 4 wt % Cr and 0.35 wt % C. The properties of this steel have been described elsewhere (16,17). Variations in prior austenite grain size from 30 to 180μm were obtained by direct oil quenching following austenitizing for one hour at temperatures between 870 and 1200°C. The steel was subsequently tested in the as-quenched, untempered condition. Microstructural parameters and ambient temperature mechanical properties are listed in Table 1.

TABLE I

Microstructural Parameters and Ambient Temperature Mechanical Properties of Structures Tested

Austenitizing Temp. (1 hr.)	Prior Austenite Grain Size (μm)	Monotonic Yield Stress (MPa)	U.T.S. (MPa)	Cyclic Yield Stress* (MPa)	% Elong. (lin. gage)	K_{IC} (MPa$\sqrt{m}$)
870°C	30	1324	1903	1480	9.2	58
1000°C	90	1324	1966	1480	7.8	76
1100°C	150	1303	1910	1470	8.3	85
1200°C	180	1324	1986	1540	3.7	79

*Cyclic yield stress represents a 0.2% offset stress measured using the incremental-step procedure (18).

Fatigue crack propagation tests were performed on 12.7 mm thick 1-T compact tension specimens, cycled under load control in a controlled environment of moist air, at 27°C with 50% relative humidity. Tests were conducted under sinusoidal tension, at 50 Hz, with a load ratio ($R = K_{min}/K_{max}$) of 0.05, where K_{max} and K_{min} are the maximum and minimum stress intensities during each cycle. Plane strain conditions were maintained throughout. Crack growth rates were continuously monitored using the elctrical potential method (19), to an accuracy of at least 0.1 mm on absolute crack length. The threshold stress intensity for crack growth (ΔK_0) was determined in terms of the alternating stress intensity ($\Delta K = K_{max} - K_{min}$) at which no growth could be detected within 10^7 cycles. Relative to the accuracy of the crack monitoring technique, this corresponds to a threshold defined in terms of a maximum crack growth rate less than 10^{-8} mm/cycle (4×10^{-10} in/cycle). Thresholds were approached using a successive reduction in load followed by crack growth procedure, as described in detail elsewhere (15,20).

RESULTS AND DISCUSSION

The mechanical properties of Fe-Cr-C steel, listed in Table I, indicate that the monotonic yield strength of this steel in the as-quenched condition is independent of austenitizing temperature, and thus prior austenite grain size. The cyclic yield stress is also largely unchanged, and can be seen to be around 11% higher than monotonic values, indicating cyclic hardening characteristic of untempered and lightly tempered martensitic steels (18). The fatigue crack propagation results for these structures are shown in Fig. 1. For the "mid-range" of growth rates exceeding 10^{-5} mm/cycle, it is apparent that propagation rates are totally independent of prior austenite grain size over the range studied. This is consistent with the fact that fatigue crack propagation behavior in steels over this growth-rate regime is largely insensitive to microstructure (e.g., 13,15,21). At lower, near-threshold growth rates, below 10^{-5} mm/cycle, resistance to fatigue crack propagation is <u>decreased</u> as as the grain size is coarsened. Not only are near-threshold crack growth rates higher but the threshold ΔK_0 is reduced from 4.4 to 3.0 MPa$\sqrt{m}$ when the prior austenite grain size is raised from 30 to 180μm. This behavior is somewhat different to that observed previously for ultra-high strength steel where coarsening the prior austenite grain size (at constant strength) in cyclically softening 300-M steel led to a decrease in near-threshold growth rates with no change in ΔK_0 (13). The effect in both cases, however, is small. More importantly, these results for high strength steels are in direct contrast to results (10,11) for much lower strength steels (less than 500 MPa) where coarsening the ferrite grain size from 20 to 150μm led to a marked increase in ΔK_0 from 7 to 17 MPa$\sqrt{m}$ (Fig. 2). As mentioned above, the latter results cannot be regarded as convincing proof of a grain size effect because of significant softening, in low strength steel, with grain coarsening (Table II) which is known to increase the threshold. The present results indicate that where strength is held constant, the grain size effect on near-threshold fatigue behavior is small, and for the present steel resistance to crack growth is improved by grain refinement.

The reasons for this marked difference in near-threshold fatigue behavior in low and high strength steels are not clear at this time. It is perhaps unsound to make comparisons between variations in ferrite grain size with those in prior austenite grain size when the controlling microstructural parameters for near-threshold crack growth are unknown. Furthermore, increases in the austenitizing temperature may lead to other microstructural changes (17), such as coarsening the martensitic packet diameter (22), or changing the distribution and grain boundary coverage of residual impurity elements (23,24), in addition to enlarging the austenite grain size. Such factors may have a profound influence on the environmental sensitivity to cracking, and thus on the resistance to near-threshold fatigue crack growth in moist air for high strength steels. The influence of impurity distribution is considered to be of particular significance in view of the large proportion of intergranular facets observed during near-threshold fatigue crack propagation in the present steel (see also Reference 20). These effects will be considered in a forthcoming publication (25).

TABLE II

Reported Values of Threshold ΔK_0 for Steels of Varying Strength and Grain Size

Steel	Monotonic Yield Stress (MPa)	Grain Size* (μm)	ΔK_0 at R = 0.05 (MPa$\sqrt{m}$)	Reference(s)
Low Strength				
1500 - X**	218	19	7.6	(10,11)
	192	40	9.8	
	168	152	17.4	
ZX**	245	64	10.6	(11)
	206	87	14.1	
	172	134	16.0	
X - 2**	402	9.9	8.6	(11)
	477	7.5	10.4	
	430	8.3	7.5	
	493	6.9	6.7	
High Strength				
300 - M	1737	20	3.1	(13)
	1657	160	3.0	
Fe-Cr-C	1324	30	4.4	
	1324	90	3.4	
	1303	150	3.3	
	1324	180	3.0	

* Ferrite grain size in low strength steels, prior austenite grain size in high strength steels.

**Grade of steels not reported, compositions between AISI 1007 and AISI 1080.

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CONCLUSIONS

From studies of fatiuge crack propagation in a cyclic hardening, as-quenched, high strength steel (Fe-Cr-C), tested at a constant strength in ambient temperature moist air, the following conclusions can be made:

1. Variations in prior austenite grain size from 30 to 180μm, induced by changing the austenitizing temperature, have no effect on the "mid-range" of growth rates exceeding 10^{-5} mm/cycle, consistent with the lack of microstructural influence on crack propagation generally observed for steels in this growth rate region.
2. The consequence of this coarsening of prior austenite grain size on near-threshold fatigue crack propagation (10^{-5} to 10^{-8} mm/cycle) is to increase crack rates, and to reduce the threshold stress intensity (ΔK_0) from 4.4 to 3.0 MPa$\sqrt{m}$.
3. Despite claims in the literature to the contrary (10-12), coarsening the grain size does not appear to be a universal means of improving near-threshold fatigue crack growth resistance in steels.

ACKNOWLEDGEMENTS

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FIGURE CAPTIONS

Fig. 1. Effect of prior austenite grain size on fatigue crack growth in Fe-Cr-C high strength steel.

Fig. 2. Variation of threshold ΔK_0 with grain size for high and low strength steels.

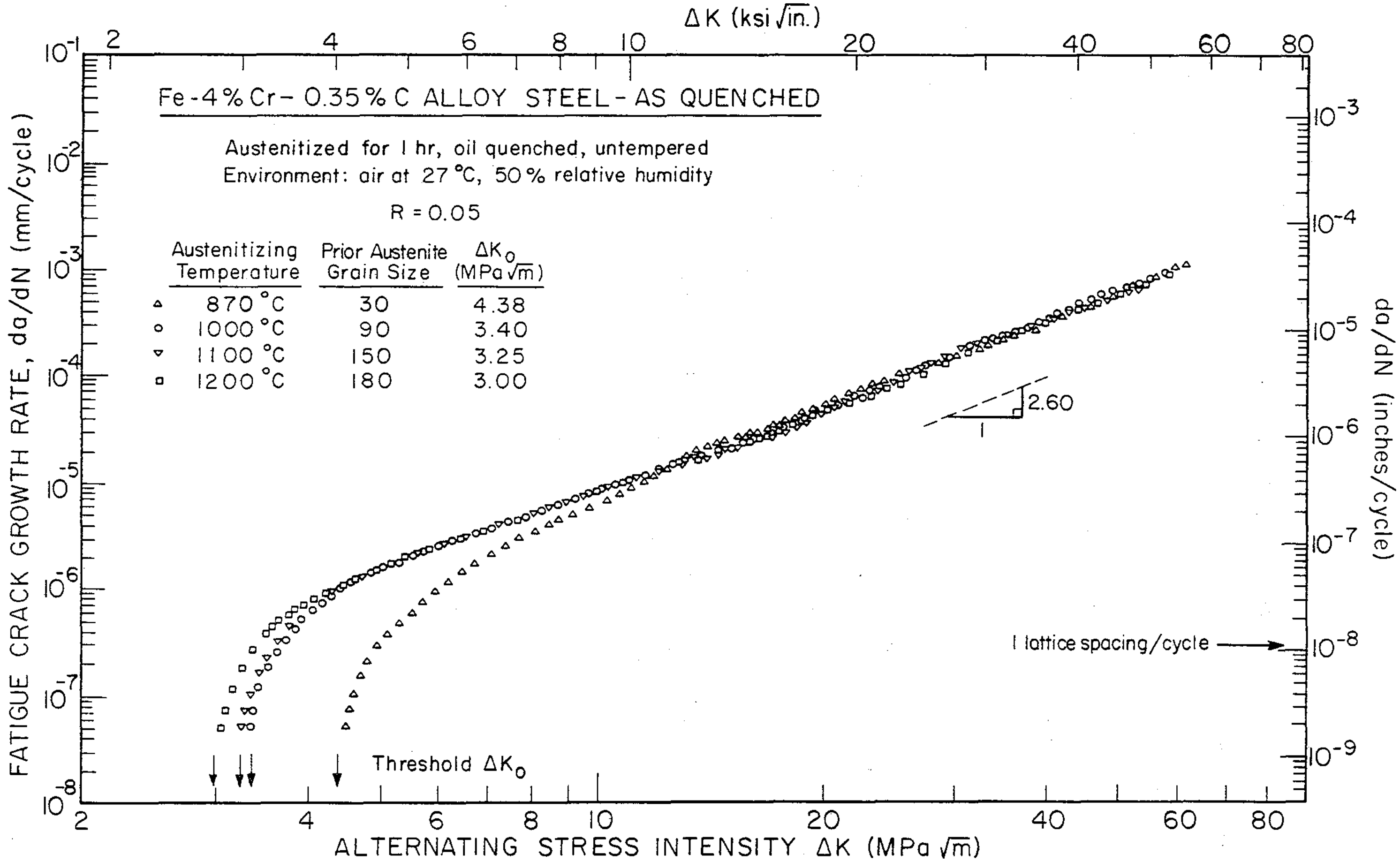

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Fig. 1

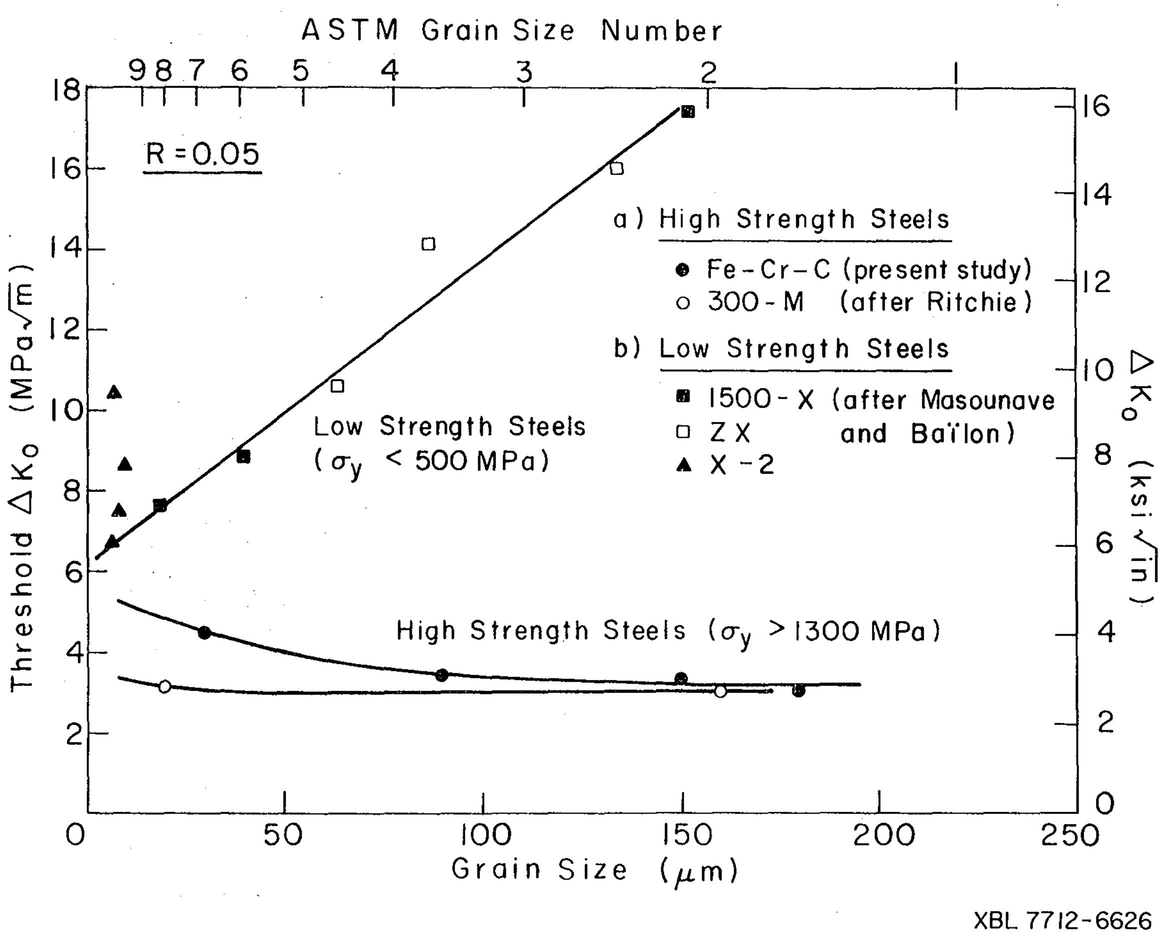
ASTM Grain Size Number
9 8 7 6 5 4 3 2 1
R = 0.05
a) High Strength Steels
● Fe-Cr-C (present study)
○ 300-M (after Ritchie)
b) Low Strength Steels
■ 1500-X (after Masounave
□ ZX and Baïlon)
▲ X-2
Low Strength Steels
(σ_y < 500 MPa)
High Strength Steels (σ_y > 1300 MPa)
Threshold ΔK_o (MPa$\sqrt{m}$)
ΔK_o (ksi$\sqrt{in}$)
Grain Size (μm)
0 50 100 150 200 250
2 4 6 8 10 12 14 16 18
0 2 4 6 8 10 12 14 16
XBL 7712-6626

Fig. 2

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