Title

FATIGUE RESISTANCE AND MICROSTRUCTURE OF EXPERIMENTAL DUAL PHASE Fe/2Si/0.lC STEEL

Author

Dutta, V.B.

Publication Date

1983-09-01

Lawrence Berkeley Laboratory
UNIVERSITY OF CALIFORNIA

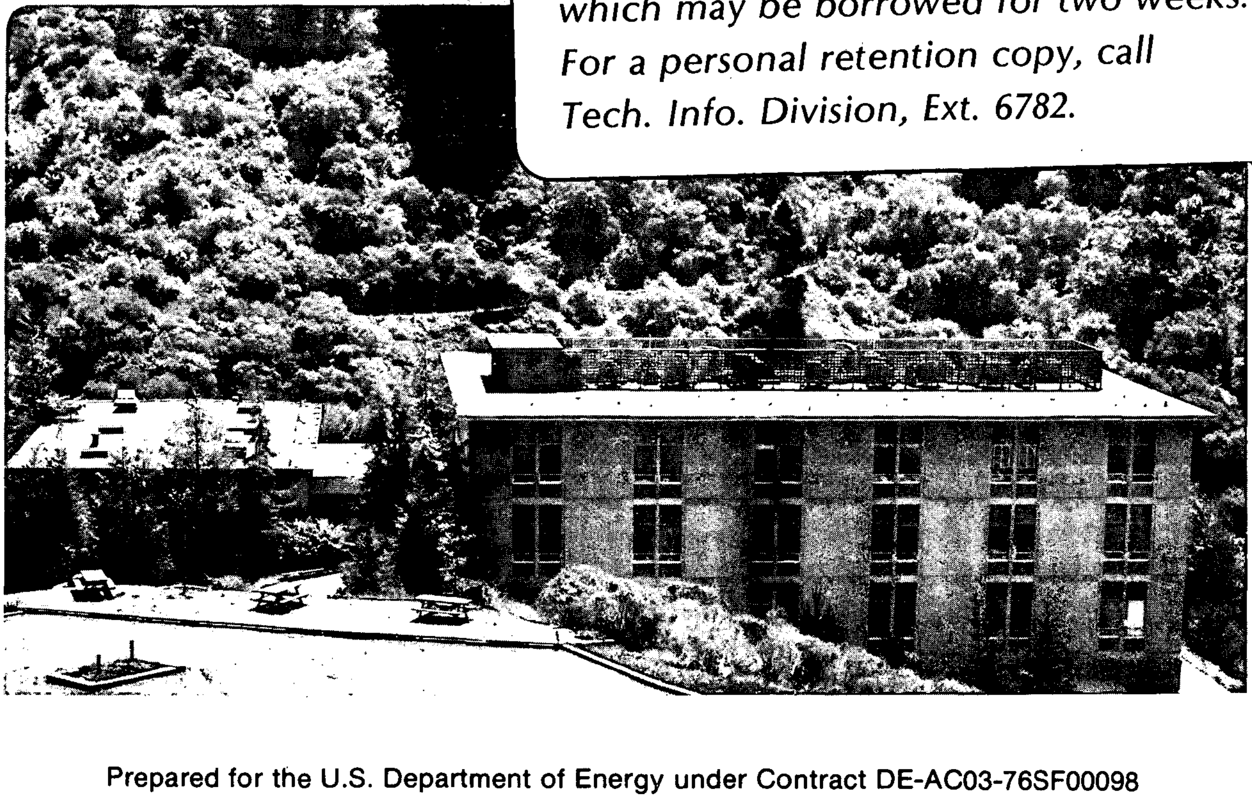
Materials & Molecular Research Division

To be presented at the International Conference on Fracture Prevention in Energy and Transport Systems, Rio de Janeiro, Brazil, November 27 - December 2, 1983

FATIGUE RESISTANCE AND MICROSTRUCTURE OF EXPERIMENTAL DUAL PHASE Fe/2Si/0.1C STEEL

V.B. Dutta, S. Suresh, G. Thomas, and R.O. Ritchie

September 1983



Prepared for the U.S. Department of Energy under Contract DE-AC03-76SF00098

DISCLAIMER

LBL-16681

FATIGUE RESISTANCE AND MICROSTRUCTURE OF EXPERIMENTAL DUAL PHASE Fe/2Si/0.1C STEEL

V. B. Dutta,[*] S. Suresh,[**] G. Thomas[*] and R. O. Ritchie[*]

[*]Materials and Molecular Research Division, Lawrence Berkeley Laboratory,
and Department of Materials Science and Mineral Enineering,
University of California, Berkeley, CA 94720

[**]Division of Engineering, Brown University, Providence, RI 02912,
formerly with the University of California, Berkeley

This work was supported by the Director, Office of Energy Research, Office of Basic Energy Sciences, Materials Science Division of the U.S. Department of Energy under Contract No. DE-AC03-76SF00098.

LBL-16681

FRACTURE PREVENTION IN ENERGY AND TRANSPORT SYSTEMS

FATIGUE RESISTANCE AND MICROSTRUCTURE OF EXPERIMENTAL DUAL PHASE Fe/2Si/0.1C STEEL

V. B. Dutta,* S. Suresh,** G. Thomas* and R. O. Ritchie*

The fatigue behavior of an experimental dual phase Fe/2Si/0.1C steel has been examined as a function of constituent morphology with the objective of developing ferritic-martensitic microstructures with optimum strength and fatigue crack propagation resistance. Microstructures containing fine globular or coarse martensite within a coarse-grained ferritic matrix were found to show the highest fatigue threshold stress intensity range ΔK_0 values reported to date (to our knowledge) and certainly the highest combination of strength and ΔK_0 for steels (ΔK_0 values above 19 $MPa\sqrt{m}$ with yield strengths in excess of 600 MPa). Such unusually high crack growth resistance is attributed primarily to a meandering crack path morphology which promotes slower crack extension rates from crack deflection and roughness-induced crack closure mechanisms.

INTRODUCTION

A number of factors have triggered intensive development programs resulting in the introduction of new steel compositions and processing techniques. The need for economical higher strength steels with good formability in transportation industries to achieve weight reductions and fuel savings as well as today's energy and resource conservation requirements are among the factors generating strong incentives to produce better steels than those in general use at minimum cost penalty.

The search for an alternative has spurred the recent development of duplex (dual phase, low carbon), ferritic-martensitic steels (1-6). These are a new class of HSLA steels whose approach to strengthening contrasts markedly with microalloyed HSLA steels in chemistry as well as processing technique (3,4). Interest in duplex ferritic-martensitic (DFM) steels has arisen since:

(1) The required composite microstructure can be produced solely by simple heat treatment, involving quenching from the two phase ($\alpha + \gamma$) field.

(2) A wide range of attractive strength and ductility combinations are obtainable.

---

*Department of Materials Science and Mineral Engineering, and Lawrence Berkeley Laboratory, University of California, Berkeley, CA 94720, U.S.A.

**Division of Engineering, Brown University, Providence, RI 02912, U.S.A., formerly with the University of California, Berkeley.

(3) Carbide forming elements, as in commercial HSLA steels, are not required (2,6).

The major source of strengthening in the DFM structure arises from the incorporation of inheritantly strong martensite as a load carrying constituent in a soft ferrite matrix which supplies the system with the essential element of ductility. The resulting mixture is analogous to that of a composite but which is obtained solely by heat treatment. Recent research work has emphasized the morphology of the ferrite-martensite microstructure especially with regard to fracture behavior (7). On the other hand, very little work has been reported on the fatigue properties especially with regard to the influence of microstructure and morphology (8-14). One study (11,12) of the fatigue crack propagation of dual phase steels indicated, however, that such duplex microstructures have the potential for extremely good crack growth resistance in that very high fatigue thresholds* were reported without sacrificing strength. Specifically, duplex structures consisting of a continuous martensite phase encapsulating islands of ferrite in an AISI 1018 mild steel were shown to have a 75% higher threshold ΔK_o value with 54% higher yield strength than conventionally normalized steel (11). In this and subsequent studies (11-14), the excellent fatigue properties of such duplex structures has been generally attributed to a meandering crack path morphology and associated crack closure effects. Consequently, the current work was undertaken to investigate whether careful control of microstructure in a well-characterized Fe/Si/C dual phase steel (2,6) could enhance these effects and result in further increased resistance to fatigue crack propagation.

EXPERIMENTAL PROCEDURES

The material selected for study was a high purity Fe/2Si/0.1C steel, of composition shown in Table 1, which was developed as a strong, ductile dual-phase steel by Thomas et al. (2,6). Following initial homogenizing at 1200°C, the alloy was given three different intercritical heat treatments chosen to achieve high martensite concentrations with varying ferrite grain sizes, but with a constant prior austenite grain size of ~240μm and constant yield strength of ~600 MPa. These heat treatment cycles and the resultant microstructures are shown in Figure 1. Corresponding quantitative metallography results (i.e., vol.% martensite, ferrite particle size, etc.) and uniaxial tensile properties are listed in Table 2. It is apparent that intermediate quenching (IQ) yields a ferritic matrix (grain size 9μm) containing a very fine fibrous martensite (58 vol.%) from the nucleation of austenite along prior martensite lath boundaries. Step quenching (SQ), on the other hand, causes ferrite to nucleate at prior austenite grain boundaries yielding a coarse-grained mixture of equiaxed martensite (32 vol.%) and ferrite (grain size 103μm). The structure resulting from the intercritical annealing process (IA) shows a finer globular martensite (44 vol.%) along ferrite grain boundaries (grain size 27μm).

Fatigue crack propagation tests were performed on 6.5mm thick compact C(T) specimens, machined following heat-treatment** in the L-T orientation,

---

*The fatigue threshold here represents the alternating stress intensity ΔK_o below which "long" fatigue cracks remain dormant or propagate at experimentally undetectable rates (15).

**A surface layer of at least 3.2mm was machined from all faces and edges to minimize problems from residual stresses induced by the final quenching.

TABLE 1 - Composition in Wt.% of Fe/2Si/0.1C Steel

C	Si	Mn	S	P	Cr	Ni	Mo	V
0.09	2.01	<0.005	<0.005	0.005	<0.005	0.06	0.03	<0.01

TABLE 2 - Quantitative Metallography and Uniaxial Tensile Properties for Fe/2Si/0.1C Dual Phase Steel

Heat Treatment	Prior Austenite Grain Size (μm)	Ferrite Particle Size (μm)	Vol. Fract. Martensite (%)	Connectivity of Martensite* (%)	Yield Strength (MPa)	UTS (MPa)	Redn. Area (%)
IQ	237	9	58	84	590	805	71
SQ	237	103	32	64	635	900	33
IA	237	27	44	82	615	827	53

*Defined as the ratio of the number of ferrite/martensite boundaries per unit length to the total number of boundaries per unit length.

and tested under load control at 50 Hz (sine wave) frequency in room temperature air (22°C, 30% relative humidity) at load ratios ($R = K_{min}/K_{max}$) of 0.05 and 0.75. Fatigue threshold stress intensities ΔK_0 were approached using manual load shedding procedures with crack lengths continuously monitored using d.c. electrical potential techniques, as described in detail elsewhere (15). In addition, macroscopic crack closure measurements were performed by monitoring the elastic compliance curves of three pairs of back-face and side-face strain gauges during the fatigue cycle. By noting the point where the load vs. relative strain plots ceased to be linear, estimates at each stress intensity range (ΔK) were made of the closure stress intensities (K_{cl}), where the crack faces became closed.

RESULTS

The variation in fatigue crack propagation rates (da/dN) with alternating stress intensity ($\Delta K = K_{max} - K_{min}$) for the IQ, SQ and IA duplex microstructures in Fe/2Si/0.1C steel is shown in Figure 2 for load ratios of 0.05 and 0.75. It is clear that behavior in this steel at low load ratios is extremely sensitive to the ferrite-martensite morphology, although the effects are far less pronounced at R = 0.75. Specifically, in the near-threshold regime below $\sim 10^{-6}$ mm/cycle at R = 0.05, growth rates are 1 to 2 orders of magnitude slower in the SQ and IA structures, with threshold ΔK_0 values 60 to 82% higher compared to the IQ structure. Above $\sim 10^{-5}$ mm/cycle, crack growth resistance in the SQ structure is still superior to the IQ structure, although growth rates in the IA structure show a much larger dependence on ΔK in this regime. At R = 0.75, the same differences in behavior exist although the magnitude of these differences is far smaller with threshold ΔK_0 values for all structures lying within the range 5 to 6 $MPa\sqrt{m}$.

Corresponding fatigue crack closure data, in terms of the ratio K_{cl}/K_{max}, is shown in Figure 3 and indicates much larger closure levels in the SQ and IA structures. For all structures, however, there is a progressively decreasing influence of such closure with increasing ΔK level. Since closure reduces the nominally applied ΔK to some lower effective level actually experienced at the crack tip (i.e., $\Delta K_{eff} = K_{max} - K_{cl}$) (16), the data in Figure 3 imply that crack extension rates in the SQ and IA microstructures are retarded the most by such closure at near-threshold levels where the influence of microstructure is maximized. At high load ratios, where there is little effect of microstructure, no influence of closure could be detected. Fatigue threshold ΔK_o values and corresponding closure data are summarized in Table 3.

TABLE 3 - Fatigue Crack Propagation Results for Fe/2Si/0.1C Dual-Phase Steel

Heat Treatment	Threshold ΔK_o		Maximum Extent of Closure K_{cl}/K_{max} at ΔK_o		Degree of Roughness*
	R = 0.05	R = 0.75	R = 0.05	R = 0.75	
	$(\mathrm{MPa}\sqrt{m})$				
IQ	10.7	4.9	0.74	0	1.03
SQ	17.1	5.1	0.83	0	1.15
IA	19.5	5.7	0.78	0	1.09

*Expressed as the ratio of the true (total) length of crack to the projected length on the plane of maximum tensile stress.

Optical and scanning electron microscopy of the crack path and fracture surface morphologies revealed that the IQ structure showed a comparatively smooth, transgranular fracture surface with an approximately linear crack path along the plane of maximum tensile stress (Fig. 4a). In contrast, the coarser SQ and IA microstructures showed very rough fracture surfaces with frequent evidence of significant crack deflections, principally at ferrite/ferrite and ferrite/martensite interfaces, resulting in far more tortuous crack paths (Fig. 4). Measurements of the degree of fracture surface roughness (Table 3), expressed as the ratio of the true (total) length of crack to the projected length, indicate, for example, the SQ structure to be many times rougher than the IQ structure. This effect was more pronounced as the threshold was approached and its occurrence could be correlated with increased closure loads (Fig. 3).

At higher ΔK levels above 10^{-5} mm/cycle, isolated brittle cleavage cracking through ferrite grains was observed in the IA structure resulting in accelerated fatigue crack propagation rates for this microstructure in this higher growth rate regime (c.f., Fig. 2).

DISCUSSION

It is apparent from the present, and previous (11-13), studies on dual phase, low carbon steels that duplex ferrite/martensite microstructures can have a profound effect on fatigue crack propagation behavior over the entire spectrum of growth rates from threshold levels to instability. A survey of the salient microstructural features contributing to such variations in crack growth resistance in dual phase structures at threshold levels is shown in Figure 5,

TABLE 1 - Composition in Wt.% of Fe/2Si/0.1C Steel

C	Si	Mn	S	P	Cr	Ni	Mo	V
0.09	2.01	<0.005	<0.005	0.005	<0.005	0.06	0.03	<0.01

TABLE 2 - Quantitative Metallography and Uniaxial Tensile Properties for Fe/2Si/0.1C Dual Phase Steel

Heat Treatment	Prior Austenite Grain Size (μm)	Ferrite Particle Size (μm)	Vol. Fract. Martensite (%)	Connectivity of Martensite* (%)	Yield Strength (MPa)	UTS (MPa)	Redn. Area (%)
IQ	237	9	58	84	590	805	71
SQ	237	103	32	64	635	900	33
IA	237	27	44	82	615	827	53

*Defined as the ratio of the number of ferrite/martensite boundaries per unit length to the total number of boundaries per unit length.

and tested under load control at 50 Hz (sine wave) frequency in room temperature air (22°C, 30% relative humidity) at load ratios ($R = K_{min}/K_{max}$) of 0.05 and 0.75. Fatigue threshold stress intensities ΔK_0 were approached using manual load shedding procedures with crack lengths continuously monitored using d.c. electrical potential techniques, as described in detail elsewhere (15). In addition, macroscopic crack closure measurements were performed by monitoring the elastic compliance curves of three pairs of back-face and side-face strain gauges during the fatigue cycle. By noting the point where the load vs. relative strain plots ceased to be linear, estimates at each stress intensity range (ΔK) were made of the closure stress intensities (K_{cl}), where the crack faces became closed.

RESULTS

The variation in fatigue crack propagation rates (da/dN) with alternating stress intensity ($\Delta K = K_{max} - K_{min}$) for the IQ, SQ and IA duplex microstructures in Fe/2Si/0.1C steel is shown in Figure 2 for load ratios of 0.05 and 0.75. It is clear that behavior in this steel at low load ratios is extremely sensitive to the ferrite-martensite morphology, although the effects are far less pronounced at R = 0.75. Specifically, in the near-threshold regime below $\sim 10^{-6}$ mm/cycle at R = 0.05, growth rates are 1 to 2 orders of magnitude slower in the SQ and IA structures, with threshold ΔK_0 values 60 to 82% higher compared to the IQ structure. Above $\sim 10^{-5}$ mm/cycle, crack growth resistance in the SQ structure is still superior to the IQ structure, although growth rates in the IA structure show a much larger dependence on ΔK in this regime. At R = 0.75, the same differences in behavior exist although the magnitude of these differences is far smaller with threshold ΔK_0 values for all structures lying within the range 5 to 6 MPa$\sqrt{m}$.

Corresponding fatigue crack closure data, in terms of the ratio K_{cl}/K_{max}, is shown in Figure 3 and indicates much larger closure levels in the SQ and IA structures. For all structures, however, there is a progressively decreasing influence of such closure with increasing ΔK level. Since closure reduces the nominally applied ΔK to some lower effective level actually experienced at the crack tip (i.e., $\Delta K_{eff} = K_{max} - K_{cl}$) (16), the data in Figure 3 imply that crack extension rates in the SQ and IA microstructures are retarded the most by such closure at near-threshold levels where the influence of microstructure is maximized. At high load ratios, where there is little effect of microstructure, no influence of closure could be detected. Fatigue threshold ΔK_0 values and corresponding closure data are summarized in Table 3.

TABLE 3 - Fatigue Crack Propagation Results for Fe/2Si/0.1C Dual-Phase Steel

Heat Treatment	Threshold ΔK_0 (MPa$\sqrt{m}$)		Maximum Extent of Closure K_{cl}/K_{max} at ΔK_0		Degree of Roughness*
	R = 0.05	R = 0.75	R = 0.05	R = 0.75	
IQ	10.7	4.9	0.74	0	1.03
SQ	17.1	5.1	0.83	0	1.15
IA	19.5	5.7	0.78	0	1.09

*Expressed as the ratio of the true (total) length of crack to the projected length on the plane of maximum tensile stress.

Optical and scanning electron microscopy of the crack path and fracture surface morphologies revealed that the IQ structure showed a comparatively smooth, transgranular fracture surface with an approximately linear crack path along the plane of maximum tensile stress (Fig. 4a). In contrast, the coarser SQ and IA microstructures showed very rough fracture surfaces with frequent evidence of significant crack deflections, principally at ferrite/ferrite and ferrite/martensite interfaces, resulting in far more tortuous crack paths (Fig. 4). Measurements of the degree of fracture surface roughness (Table 3), expressed as the ratio of the true (total) length of crack to the projected length, indicate, for example, the SQ structure to be many times rougher than the IQ structure. This effect was more pronounced as the threshold was approached and its occurrence could be correlated with increased closure loads (Fig. 3).

At higher ΔK levels above 10^{-5} mm/cycle, isolated brittle cleavage cracking through ferrite grains was observed in the IA structure resulting in accelerated fatigue crack propagation rates for this microstructure in this higher growth rate regime (c.f., Fig. 2).

DISCUSSION

It is apparent from the present, and previous (11-13), studies on dual phase, low carbon steels that duplex ferrite/martensite microstructures can have a profound effect on fatigue crack propagation behavior over the entire spectrum of growth rates from threshold levels to instability. A survey of the salient microstructural features contributing to such variations in crack growth resistance in dual phase structures at threshold levels is shown in Figure 5, taken from the current work and from data in references 11-13 on Fe/2Si/0.1C and mild steels. Although the scatter in individual data points is large, the trends are clear in that optimum near-threshold crack growth resistance is achieved with coarser prior austenite grain sizes, coarser ferrite grain sizes, and a martensite phase of intermediate volume fractions (i.e., ~40%) with high connectivity. It is pertenent to note, however, that such marked microstructural effects are only apparent at low load ratios. As the current study shows (Fig. 5), at $R = 0.75$ the variation in ΔK_0 with microstructural variations is in comparison almost negligible.

Such a result is totally consistent with the notion that the superior crack growth resistance of certain duplex microstructures at low load ratios results from enhanced fatigue crack closure (12-14). It is apparent from the present study that the structures showing the best near-threshold crack growth resistance (Fig. 2), namely SQ and IA, show the highest magnitude of closure (Fig. 3), and the most tortuous crack paths (Fig. 4) involving marked crack deflections leading to rough fracture surfaces (Table 3). The IQ structure, which displays 1-2 orders of magnitude faster growth rates close to ΔK_0, in contrast shows lower closure levels (Fig. 3) and a more linear crack path.

This association between increased crack growth resistance with a meandering crack path is consistent with the concept of a reduced near-tip driving force for crack advance due to crack deflection (14,17) and associated roughness-induced crack closure (12-14,17-21). As noted elsewhere (17), the mere deflection of a fatigue crack from the plane of maximum tensile stress can both decrease the local Mode I stress intensity range at the crack tip and increase the total distance the crack must travel, thus effectively retarding the crack growth rate. For example, deflecting a planar crack through an angle of 60° yields typically a 12% lower stress intensity at the tip. However, more importantly, at stress intensity ranges where the crack tip opening displacements are comparable with the scale of fracture surface roughness (i.e., at near-threshold levels), such deflections induce a Mode II stress intensity at the tip, thereby enhancing the crack tip shear displacements. Under inelastic conditions with limited reversibility of slip (i.e., where fracture surfaces become oxidized), such shear displacements effectively wedge the crack open at contact points between asperities thereby promoting roughness-induced crack closure and effectively retarding the crack growth rate (18-21). However, at high load ratios where crack tip opening displacements are large enough to inhibit such contact, closure effects will be minimal consistent with the zero K_{cl}/K_{max} measurements (Fig. 3) and the much reduced role of microstructure (Fig. 2). Quantitative estimates of the relative effects of deflection and roughness-induced closure have been presented elsewhere (14), based on simple modelling studies (17,21) for these phenomena.

Finally, it is interesting to note that classical smooth bar endurance strength studies, or studies involving the growth of microstructurally-short cracks (9,10), have not shown the same usually large and beneficial effects of certain duplex microstructures, reported for long crack propagation tests. This observation is consistent with the conclusion that the primary influence of dual phase microstructures on crack growth behavior arises through closure mechanisms. Similar to high load ratio testing, crack closure mechanisms have far less effect on short cracks, because such closure acts in the wake of the crack tip and by definition short cracks possess only a limited wake (e.g., refs. 22 and 23).

CONCLUDING REMARKS

By employing the notion of improving fatigue properties by promoting crack path morphologies to enhance crack deflection and roughness-induced crack closure, duplex ferritic-martensitic microstructures in an experimental dual phase Fe/2Si/0.1C steel have been developed with unusually high resistance to fatigue crack propagation. Specifically, the coarser grained SQ and IA structures show low load ratio threshold ΔK_0 values as high as 17.1 and 19.5 MPa$\sqrt{m}$, respectively, in a steel with yield strength in excess of 600 MPa. To our knowledge these values are the highest fatigue thresholds reported to date, and perhaps more importantly the highest combination of fatigue threshold and yield strength, representing a 43 to 64 percent improvement on the next best steel (Fig. 6). In the SQ structure, this improved fatigue resistance is maintained up to growth rates as high as 10^{-3} mm/cycle, whereas the IA structure does show some tendency for cleavage cracking above $\sim 10^{-5}$mm/cycle leading to somewhat accelerated growth rates (see also refs. 13, 24).

For the majority of ferrous alloys, major increases in near-threshold fatigue resistance are only achieved by marked reductions in strength level (15). However, as noted previously (11), an exceptional quality of dual phase steels is that the higher threshold ΔK_o values can be achieved with microstructures which do not result in loss in strength. However, it is important to note that the primary source of such usually high fatigue resistance is the increased crack deflection and closure levels resulting from a tortuous crack path. Thus the main effect of duplex microstructures will be seen on the propagation of long cracks at low load ratios. In tests involving high mean stresses, crack initiation or the growth of short (micro-) cracks, fatigue crack closure mechanisms will be far less potent and accordingly the beneficial influence of duplex microstructures will be much reduced. This research has shown the significance of controlling the morphology of the constituents in order to achieve superior combinations of tensile and fatigue properties - a factor previously noted for non-cyclic fracture behavior (7).

ACKNOWLEDGEMENTS

This work, which was performed in partial fulfillment of the M.S. degree for V. B. Dutta, was supported by the Director, Office of Energy Research, Office of Basic Energy Sciences, Materials Science Division of the U.S. Department of Energy under Contract No. DE-AC03-76SF00098.

REFERENCES

1. Hayami, S., and Furikawa, T., 1977 "Microalloying 75", Union Carbide, New York.

2. Koo, J. Y., and Thomas, G., 1977, Metallurgical Transactions A 8A, 525.

3. Koo, J. Y., and Thomas, G., 1976, Materials Science and Engineering 24, 187.

4. Kot, R. A., and Morris, J. W., eds., 1977 "Structure and Properties of Dual Phase Steels", The Metallurgical Society of AIME, Warrendale, PA.

5. Davenport, A. T., ed., 1977 "Formable HSLA and Dual Phase Steels", The Metallurgical Society of AIME, Warrendale, PA.

6. Thomas, G., and Koo, J. Y., 1977 "Structure and Properties of Dual Phase Steels", The Metallurgical Society of AIME, Warrendale, PA, p. 183; and 1977 "Formable HSLA and Dual Phase Steels", The Metallurgical Society of AIME, Warrendale, PA, p. 40.

7. Kim, N. J., and Thomas, G., 1981, Metallurgical Transactions A 12A, 483; see also Koo, J. Y., and Thomas, G., 1979, Scripta Met. 13, 1141.

8. Davies, R. G., and McGee, C., 1977 "Structure and Properties of Dual Phase Steels", The Metallurgical Society of AIME, Warrendale, PA, p. 1.

9. Kunio, T., and Yamada, K., 1979 "Fatigue Mechanisms", ASTM STP 675, p. 343.

10. Kunio, T., Shimizu, M., Yamada, K., and Nakabayashi, H., 1982 "Fatigue Thresholds" (Eds. J. Bäcklund, A. Blom and C. J. Beevers), EMAS Ltd., Warley, Vol. 1, p. 409.

11. Suzuki, H., and McEvily, A. J., 1979, Metallurgical Transactions A 10A, 475.

12. Minakawa, K., Matsuo, Y., and McEvily, A. J., Metallurgical Transactions A 13A, 439.

13. Wasynczuk, J. A., Ritchie, R. O., and Thomas, G., 1983, Materials Science and Engineering, in press.

14. Dutta, V. B., Suresh, S., and Ritchie, R. O., 1983, Metallurgical Transactions A, in review.

15. Ritchie, R. O., 1979, International Metals Reviews 20, 205.

16. Elber, W., 1971 "Defect-Tolerance in Airframe Structures", ASTM STP 486, p. 230.

17. Suresh, S., 1983, Metallurgical Transactions A 14A, in press.

18. Walker, N., and Beevers, C. J., 1979, Fatigue of Engineering Materials and Structures 1, 135.

19. Minakawa, K., and McEvily, A. J., 1981, Scripta Metallurgica 15, 633.

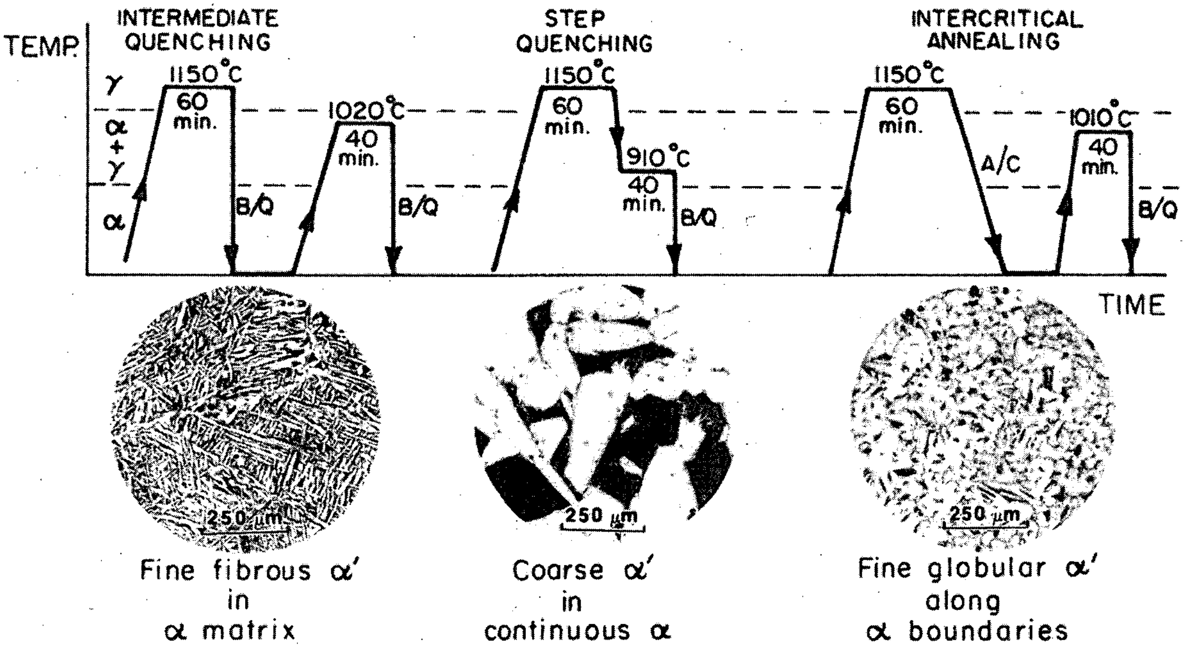
20. Ritchie, R. O., and Suresh, S., 1982, Metallurgical Transactions A 13A, 937.

21. Suresh, S., and Ritchie, R. O., 1982, Metallurgical Transactions A 13A, 1627.

22. Schijve, J., 1982 "Fatigue Thresholds" (Eds. J. Bäcklund, A. Blom and C. J. Beevers), EMAS Ltd., Warley, Vol. 2, p. 881.

23. Suresh, S., and Ritchie, R. O., 1983, International Metals Reviews 24, in review.

24. Ritchie, R. O., and Knott, J. F., 1974, Materials Science and Engineering 14, 7.

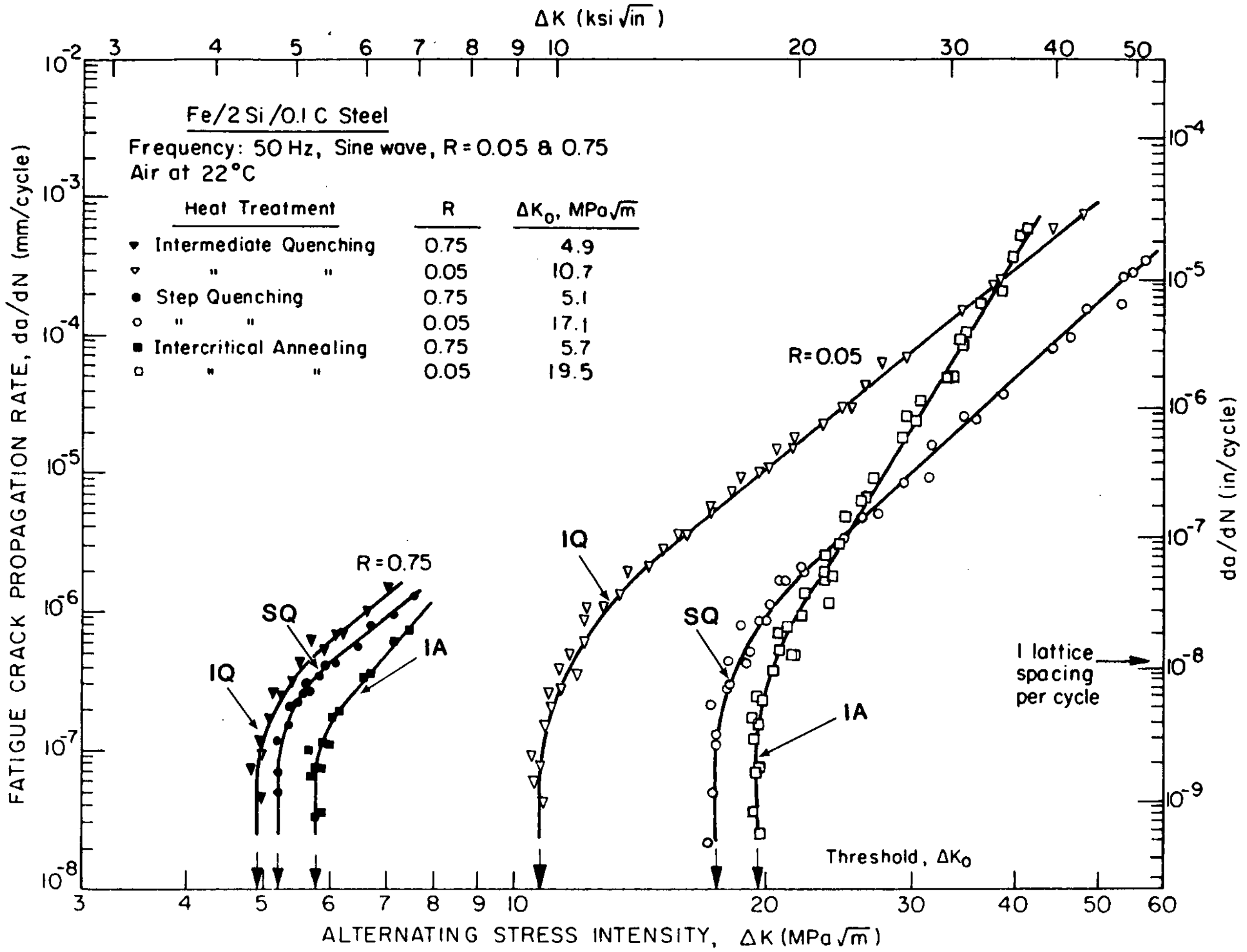


(a) HEAT TREATMENT CYCLES

(b) DUAL PHASE MICROSTRUCTURES

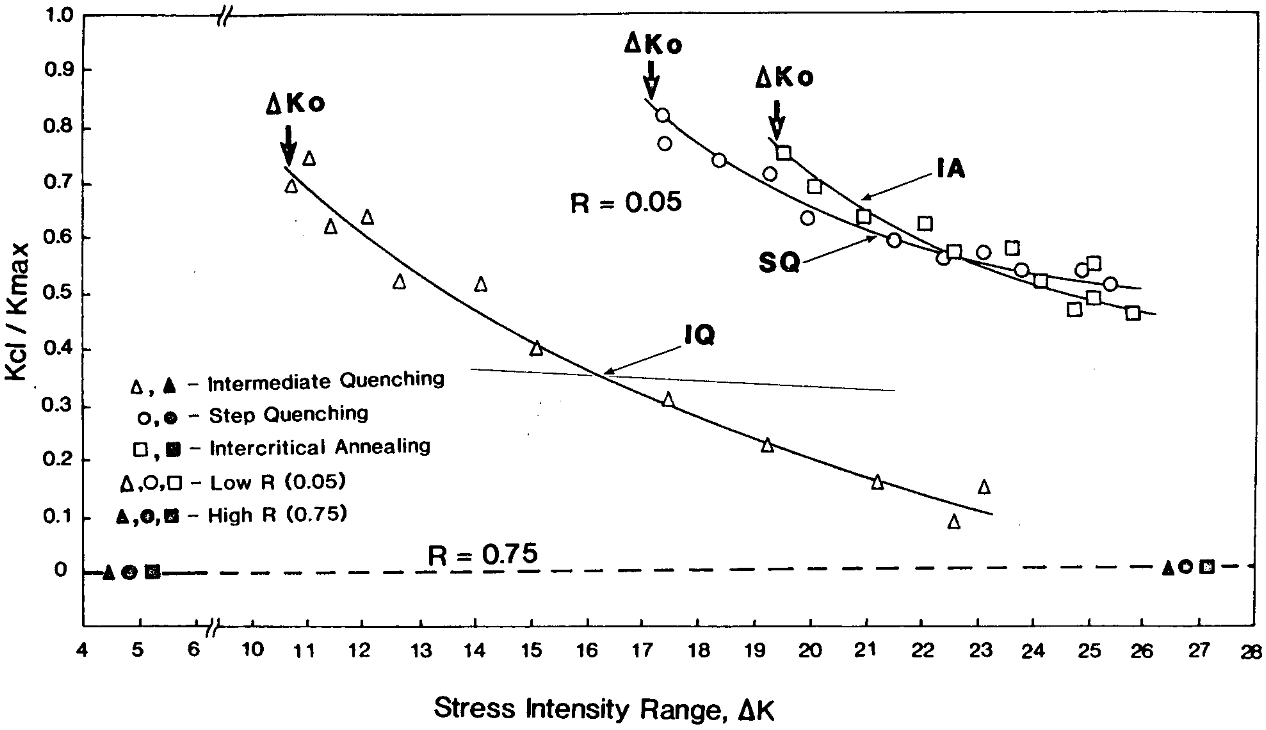
XBB 833-2300

Figure 1. Intercritical treatment cycles and resulting duplex ferritic/martensitic microstructures in Fe/2Si/0.1C steel, following intermediate quenching (IQ), step quenching (SQ) and intercritical annealing (IA).



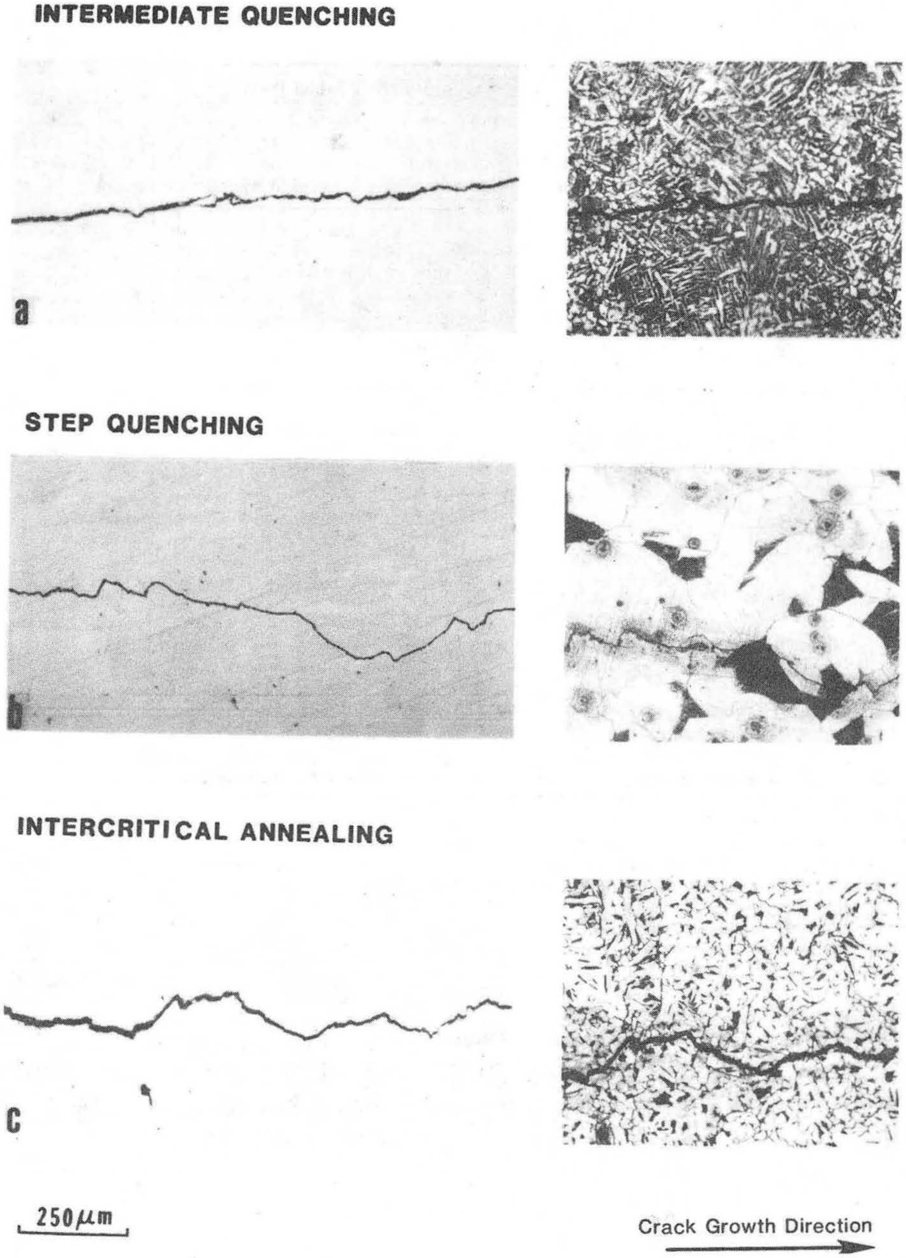
XBL 838-10897

Figure 2. Fatigue crack propagation rates (da/dN) as a function of the alternating stress intensity (ΔK) for Fe/2Si/0.1C dual phase steel with the IQ, SQ and IA microstructures. Tests at 50 Hz in room temperature air at load ratios of R = 0.05 and 0.75.



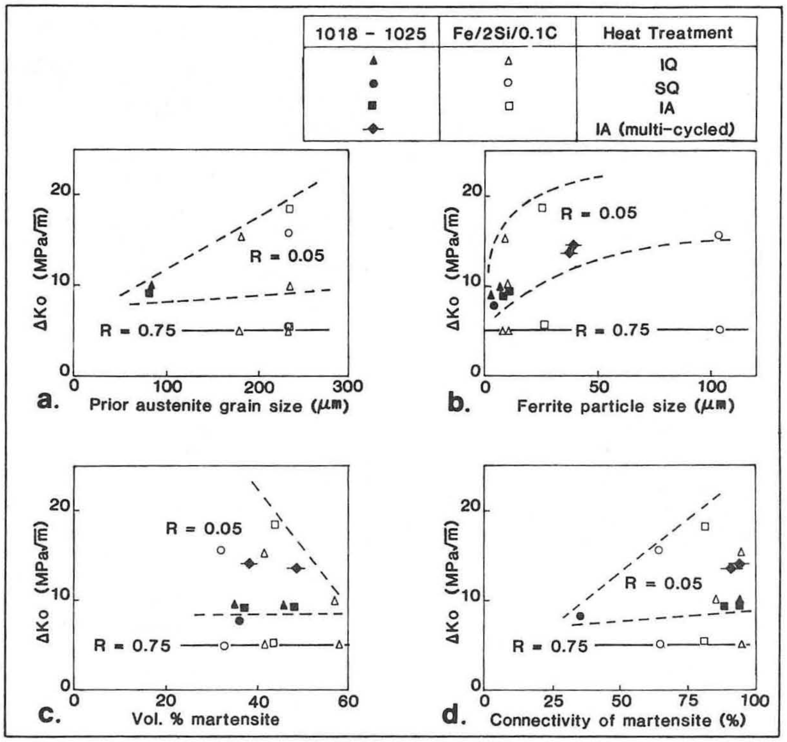
XBL 838-10896

Figure 3. Experimental crack closure measurements showing the decrease in closure stress intensity, K_{cl}, normalized with respect to K_{max}, with increasing ΔK for IQ, SQ and IA structures.



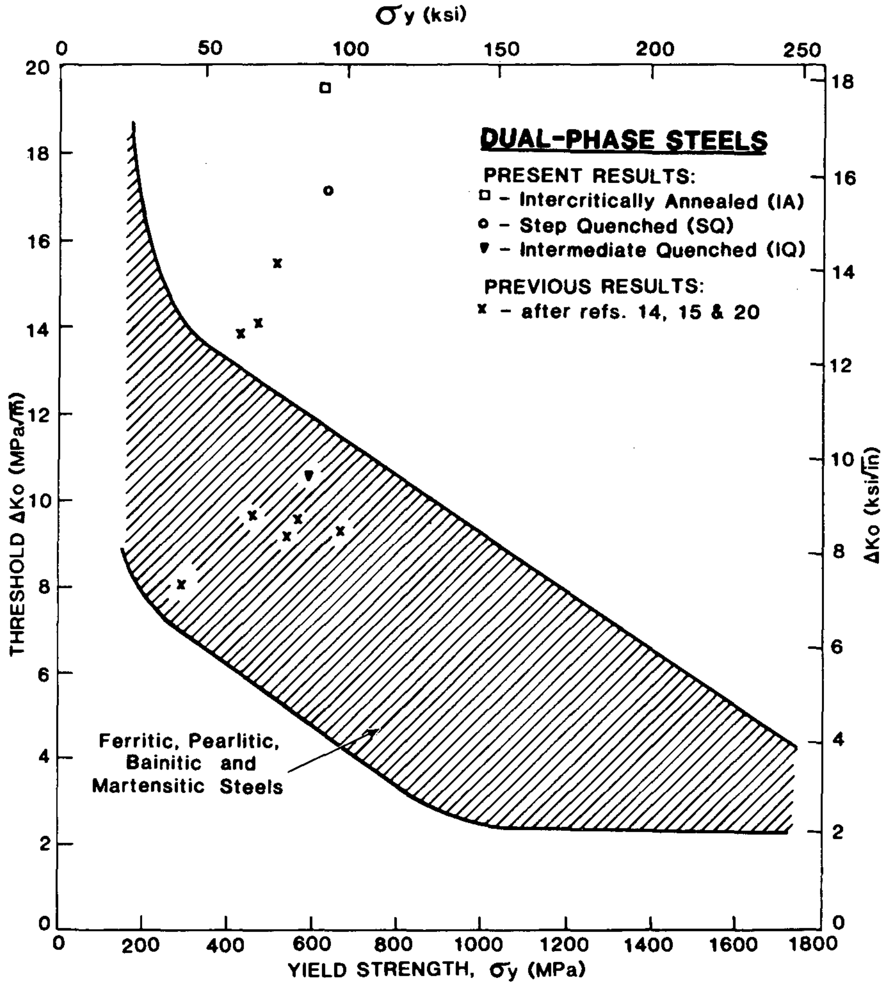
XBB 839-7928

Figure 4. Near-threshold crack path morphology showing linear crack path in IQ structure compared to meandering crack paths in SQ and IA conditions.



XBL 839-11376

Figure 5. Present and published results (refs. 11-13) on threshold fatigue behavior of Fe/2Si/0.1C and mild steels with duplex ferritic/martensitic structures. Note how ΔK_0 values at high load ratio are insensitive to microstructure.



XBL 838-10895

Figure 6. Variation of fatigue threshold stress intensity range ΔK_0 at R ∿ 0 with yield strength for ferrous alloys (from ref. 15), highlighting the usually high strength and fatigue threshold properties of dual phase steels.

TECHNICAL INFORMATION DEPARTMENT
LAWRENCE BERKELEY LABORATORY
UNIVERSITY OF CALIFORNIA
BERKELEY, CALIFORNIA 94720