JMEPEG (2006) 15:352-354
DOI: 10.1361/105994906X108684

1059-9495/$19.00

Crack Path Morphology in Dual-Phase Steel

M. Sarwar, E. Ahmad, N. Hussain, B. Ahmad, and T. Manzoor

(Submitted May 6, 2005; in revised form May 26, 2005)

Intercritical heat treatment (ICHT) and thermomechanical processing (TMP) were used on steel having 0.16% C to vary the morphology, distribution of ferrite, and martensite phases, in order to study the resistance to fatigue crack propagation and crack path morphology in dual-phase steel. A crack growth rate has been determined at ~10^{-10} to 10^{-3} m per cycle in ICHT and TMP samples. The tortuous morphology of the crack path was observed in unrolled materials, which resulted in reduction of the crack driving force from crack deflection and increased the ΔK_{th}. In thermomechanical processed materials, the crack tended to cross the martensite and the crack path become less circuitous, resulting in decrease a threshold stress intensity factor (ΔK_{th}) as compared with unrolled material.

Keywords crack path morphology, crack propagation, dual-phase steel

1. Introduction

Dual-phase steels have gained much commercial importance as structural engineering materials among high-strength low-alloy steels. These steels have outstanding combinations of compositional simplicity, high strength, and excellent formability. Their characteristic microstructure consists of 20-25% hard phase (martensite) in a relatively soft, ductile, ferrite matrix. Much research has been done regarding structure-property relationships (Ref 1-4). Despite extensive published work, adequate attention has not been paid to the analysis of path morphology of dual-phase steel.

The work described herein is an investigation into the effect of ferrite-martensite microstructures on crack path morphology.

2. Experimental Procedures

The composition of steel used for this study was as follows: C, 0.16; Si, 0.24; Mn, 1.03; Cr, 0.14; and Fe, balance.

Megalographic investigation of the as-received microstructure showed that it consisted of unbanded ferrite, pearlite, and traces of martensite or retained austenite (Fig. 1).

2.1 Heat Treatment

Blanks of 6 mm thick metal were intercritically annealed at 780 °C for 20 min and quenched into iced brine solution to produce 55% martensite. The blanks with 12 mm initial thickness were heat treated at 780 °C for 20 min, rolled to 50% reduction, and quenched into iced brine solution to produce similar amounts of martensite as mentioned above.

To study the crack path morphology, blanks 6 mm thick, 180 × 45 mm in area (for 0% reduction) and 12 mm thick, 130 × 45 mm in area (for 50% reduction) were obtained from the original plates for fatigue crack propagation tests.

2.2 Fatigue Testing

The single edge-notched tension type of specimens (Fig. 2) were machined from the processed blanks for fatigue crack growth tests. The edge notch was spark machined; both surfaces of each specimen were prepared by coarse grinding on silicon carbide paper followed by polishing with 6 and 1 μm diamond paste.

The fatigue tests were carried out using an Instron (Model 1255, UK) hydraulic testing machine. The frequency of testing was 5-50 Hz, depending upon the crack growth rate. The waveform was sinusoidal. The specimens were tested at room temperature in a normal atmosphere. The test load was parallel to the rolling direction.

For the determination of the threshold stress intensity range,

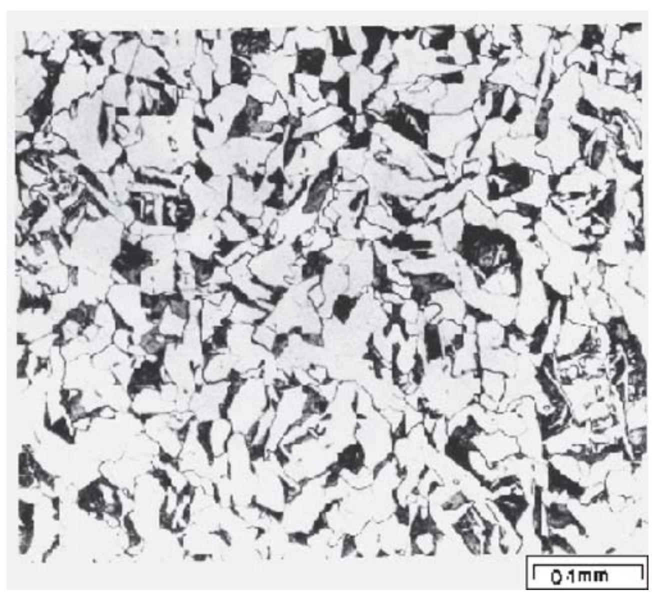

Fig. 1 Microstructure of as-received materials

M. Sarwar, E. Ahmad, N. Hussain, B. Ahmad, and **T. Manzoor,** NMD, Pakistan Institute of Nuclear Science and Technology (PINSTECH), P.O. Nilore, Islamabad, Pakistan. Contact e-mail: drmsrana@yahoo.com.

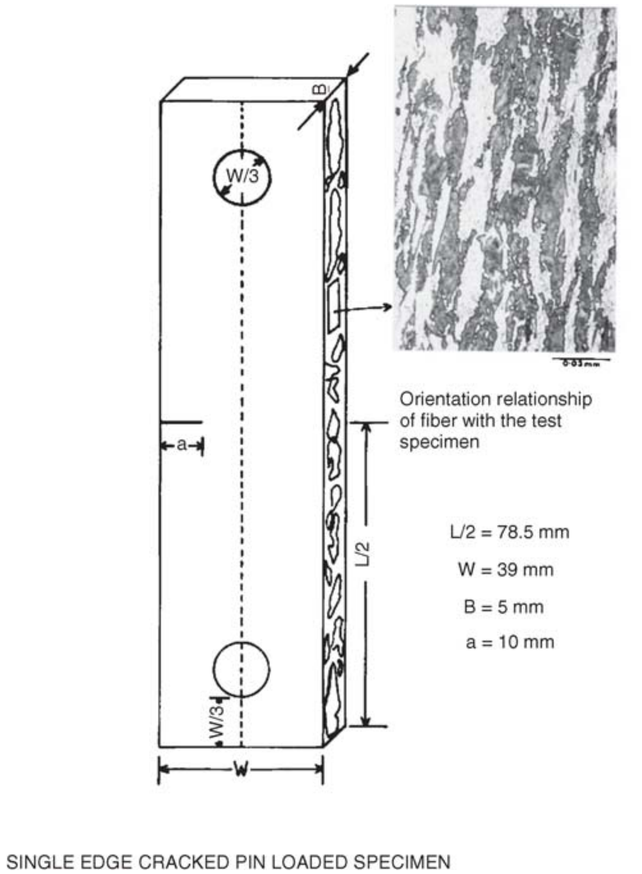

Fig. 2 Illustration of orientation relationship of fiber with the test specimen

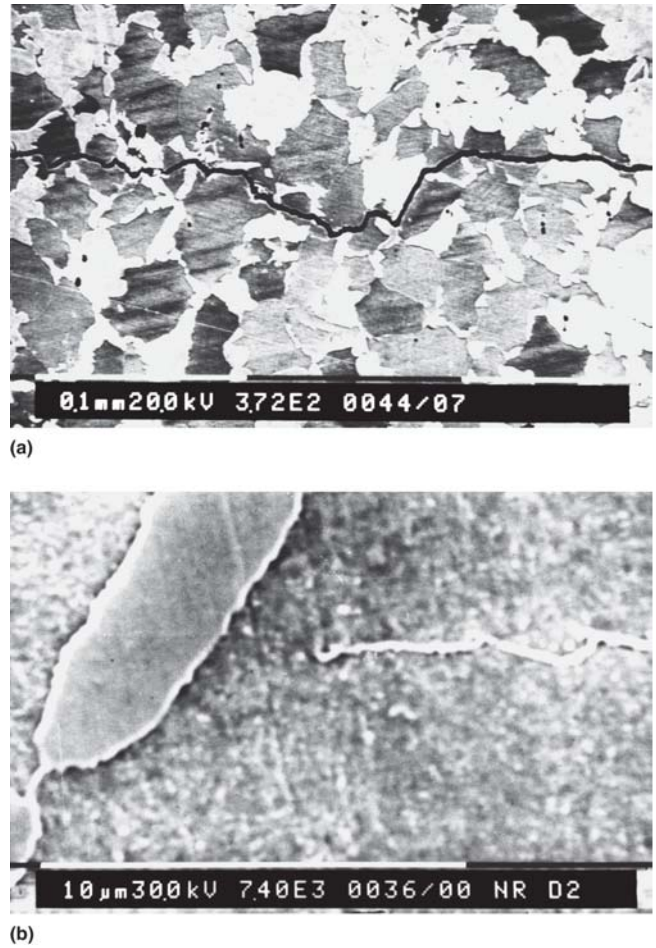

Fig. 3 (a) SEM showing fatigue crack path morphology specimen intercritically annealed at 780 °C and quenched in iced brine; (b) SEM showing crack tip, specimen intercritically annealed at 780 °C and quenched in iced brine

ΔK_{th}, a stepwise, ΔK-decreasing method was used. The crack was initially grown 1 mm from the notch tip, and the load was then progressively shed by approximately 10% of the current load level at each step. At any load level, the crack was allowed to grow beyond the plastic zone associated with the previous load level. This procedure was followed until a stress intensity range was reached (corresponding to $da/dN = 4 \times 10^{-10}$ m/cycle) at which no detectable growth occurred. This stress intensity range was designated as the threshold level, ΔK_{th}. Once the threshold value had been determined, the load was increased gradually until the termination of the test. The crack length, *a*, was measured at both surfaces of the specimen, one side by using a traveling microscope having an eye piece with an engraved scale. An SLR camera was used to take photographs of the other surface of the specimen, from which the crack length was measured. The fatigued specimens were removed from the machine, and conventional metallographic techniques were used to study the crack path morphology with a scanning electron microscope (SEM).

3. Results and Discussion

3.1 Crack Path Morphology

SEM of polished and etched sections of the specimen normal to the crack front revealed that both transgranular (through ferrite and martensite) and intergranular (along ferrite/martensite and ferrite interface) cracking occurred. Examples are shown in Fig. 3 and 4 for intercritically annealed and thermomechanically processed materials, respectively.

The mechanism of fatigue crack extension arises in the region of cyclic plastic deformation at the crack tip. When accumulated plastic strain reaches a critical level, the material at the crack tip becomes unstable and the crack extends. The ferrite is a soft phase compared with martensite in dual-phase steel. Therefore, the ferrite at the crack tip accumulates strain more rapidly, and the crack might be expected to advance within the ferrite phase. It was observed in the present work in the unrolled material that, when a crack in ferrite approached an interface with martensite its path was deflected to avoid passing through the martensite, i.e., Fig. 3(a). Presumably, insufficient cyclic deformation accumulated in the material at the crack tip for the martensite there to become unstable. Similar crack path morphology was reported in AISI 1018 steel having an unrolled dual-phase microstructure by other researchers (Ref 5-8).

Figure 3(b) shows the crack tip at threshold and suggests that at low ΔK the crack repeatedly bifurcated. At each bifurcation, the branch that continued to propagate was that which sustained the highest shear stress. The stress intensity at the end of a bifurcated crack would be expected to be less than at the end of single crack. Thus, bifurcation would tend to halt or

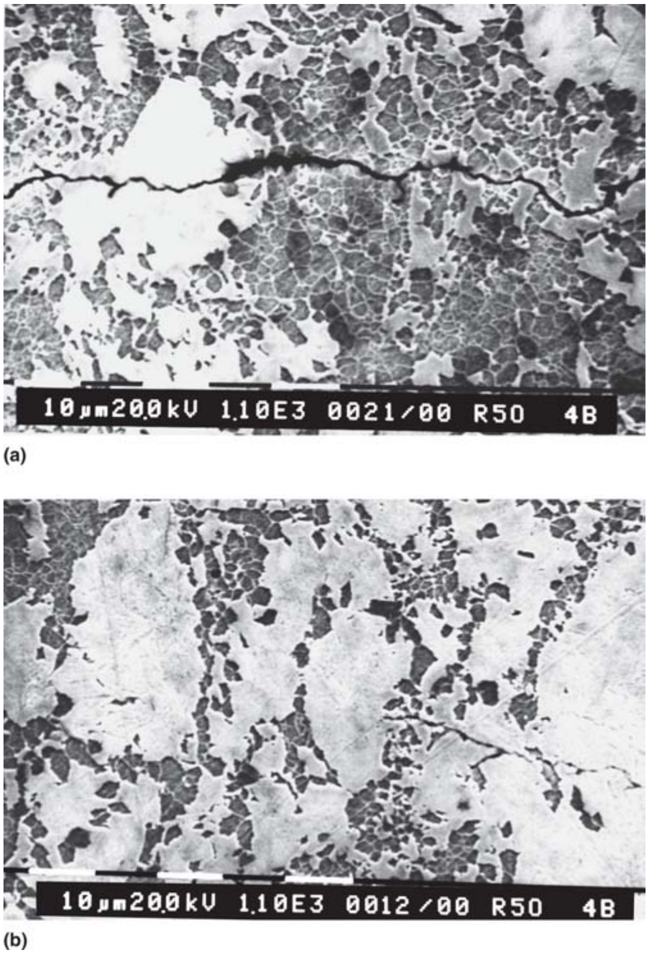

Fig. 4 (a) SEM showing fatigue crack path morphology specimen intercritically annealed at 780 °C and then rolled to 50% reduction, quenched in iced brine; (b) SEM showing crack tip, specimen intercritically annealed at 780 °C and then rolled to 50% reduction, quenched in iced brine

slow propagation in Mode I. However, at the reduced stress intensity, crack propagation may be able to continue from one of the crack tips in Mode II, that is, in shear along an active slip band. This is analogous to stage I crack propagation, in the sequence of stages proposed by Ryder and Forsyth (Ref 9) in describing the origin of fatigue failure in slip bands from flaw-free surfaces. Once bifurcation has occurred at sufficiently low $\Delta\sigma$, a reinitiation step in a slip band appears to be required to keep the crack tip. Naturally, that one of the pair of crack tips produced by bifurcation that is lying closest to the plane of maximum shear will be selected for reinitiation. After propagating in Mode II (stage I) far enough to escape the masking influence of the nonpropagating tip, the Mode II crack may realign itself to continue propagating in Mode I, normal to the applied tensile stress. Eventually, in the course of the test, $\Delta\sigma$ is lowered sufficiently for reinitiation to become impossible after bifurcation: alternatively, as suggested in Fig. 3(b), the crack tip is so near to a particle of stronger phase that, when a bifurcation appears, insufficiently shear occurs at either crack tip for the reinitiation event to take place.

Figure 4(a) and (b) show the crack path morphology at higher ΔK and at threshold in the thermomechanically processed material. The crack deviates out of the plane normal to the tensile stress only if the crack encounters a large martensite particle. It can also be seen in Fig. 4(b) that a martensite particle appeared to prefer the crack arrest site at the threshold level.

4. Conclusions

The zigzag crack path morphology was observed in unrolled material at high ΔK (stress intensity factor), and the crack tends to pass martensite grains, resulting in a less circuitous crack path in thermomechanically processed material. It should also be pointed out that the martensite particle appeared to prefer the crack arrest site at the threshold level in thermomechanically processed material.

References

1. R.G. Davies, Influence of Martensite Composition and Carbon Content on the Properties of Dual-Phase Steel, *Met. Trans.,* 1978, **9A,** p 671-679
2. J.M. Rigsbee and P.J. Vander Arend, Laboratory Studies of Microstructures and Structure-Property Relationship in Dual-Phase HSLA Steels, *Formable HSLA and Dual-Phase Steels, AIME,* A.T. Davenport, Ed., AIME, New York, 1977, p 56-86
3. J.Y. Koo and G. Thomas, Design of Duplex Low Carbon Steels for Improved Strength: Weight Applications, *Formable HSLA and Dual-Phase Steels, AIME,* A.T. Daversport, Ed., AIME, New York, 1977, p 45-55
4. D.C. Wei, Structure-Fatigue Correlation for Dual-Phase HSLA Steels Sample, *Quarterly,* 1981, **12**(4), p 24-31
5. K. Minakawa, A.J. McEvily, and Y. Matuso, The Influence of a Duplex Microstructure in Steels on Fatigue Crack Growth in the Near-Threshold Region, *Metall. Trans. A,* 1982, **13A,** p 439
6. K. Nakajima, S.M. Yokoe, and T. Miyata, The Influence of Microstructural Morphology and Prestrain on Fatigue Crack Propagation of Dual-Phase Steels in Near Threshold Region, *ISIJ Int.,* 1999, **39**(5), p 486-492
7. H. Suzuki and A.J. Meehvily, Microstructural Effects on Fatigue Crack Growth in a Low Carbon Steel, *Metall. Trans. A*, 1979, **10A,** p 475-481
8. V.B. Dutta, S. Suresh, and R.O. Ritchie, *Fatigue Crack Propagation in Dual-Phase Steels: Effects of Ferritic-Martensitic Microstructures on Crack Path Morphology,* Vol. 15A, June 1984, p 1193-1207
9. P.E.J. Forsyth and D.A. Ryder, *Metallurgica,* 1961, p 117