Influence of Martensite Volume Fraction on Fatigue Limit of a Dual-Phase Steel

M. Sarwar, R. Priestner, and E. Ahmad

(Submitted 28 October 1999; in revised form 19 March 2002)

Different dual-phase microstructures were produced in a steel containing 0.16 C (wt.%) by careful design of the heat treatment schedule in order to study the effect of microstructures, volume fraction of martensite, and epitaxial ferrite on fatigue limit. It was observed that the fatigue limit was raised by an increasing martensite content and aspect ratio, and reduced by the presence of epitaxial ferrite (new ferrite). However, these changes were very clearly and directly related to simultaneous changes in strength.

Keywords dual-phase steel, fatigue limit, martensite volume fraction

1. Introduction

Dual-phase steels have gained commercial importance as a new class of structural steel among the group of high strength, low alloy steels. They are characterized by their microstructure, which consists of 18-25% hard martensite in a soft ductile ferrite matrix. These steels are conventionally produced by annealing in the intercritical, austenite-plus-ferrite $(\alpha + \gamma)$ phase field followed by cooling at a rate sufficient to transform the optimum amount of austenite to martensite. Dual-phase steels have an outstanding combination of strength and ductility.[1-3] Despite the extensive published work, the effects in terms of microstructure and volume fractions of martensite and epitaxial ferrite on fatigue limit of dual-phase steels have not been sufficiently studied.

The purpose of this work was to investigate the influence of dual-phase microstructures on volume fraction of martensite and epitaxial ferrite on fatigue limit of dual-phase steel.

2. Experimental Procedure

The chemical composition (wt.%) of steel used for this study was as follows: Fe, balance; C, 0.16; Mn, 1.03; Cr, 0.14; Si, 0.24; and Mo, 0.04.

Each specimen was coded (e.g., 50 BQ 780) according to the treatment given. The left-hand number represents the amount of rolling deformation, the middle letters represent the cooling medium used (ice brine quenched [BQ], hot water quenched [HWQ], and oil quenched [OQ]), and the right-hand numbers represent the intercritical annealing temperature.

2.1 Heat Treatment For Mechanical Testing

For fatigue limit tests to be performed, blanks must be 6 mm thick, 180 × 45 mm in area (if no rolling is used, i.e., 0% reduction), and 12 mm thick and 130 × 45 mm in area (for rolling to 6 mm thickness, i.e., 50% reduction was obtained from the original plates). These blanks were divided into four groups for intercritical heat treatment (ICHT) and thermomechanical processing (TMP).

2.1.1 Group I The 6 mm thick blanks were intercritically annealed at 780 °C for 20 min and quenched into ice brine or hot water (86 °C) to produce 55% and 30% martensite, respectively.

2.1.2 Group II Blanks with 12 mm initial thickness were heat treated at 780 °C for 20 min, then rolled to a 50% reduction and quenched into ice brine or oil to produce the same amounts of martensite mentioned for group I.

2.1.3 Group III Blanks, as in group I, were intercritically annealed at 740 °C for 20 min to produced 30% austenite and then quenched into ice brine.

2.1.4 Group IV Blanks with the same initial thickness as those in group II were heat treated at 740 °C for 20 min, rolled to a 50% reduction, and then quenched into ice brine.

2.2 Grain Size Measurement

The average grain size was measured from photomicrographs using the mean linear intercept method. Three concen-

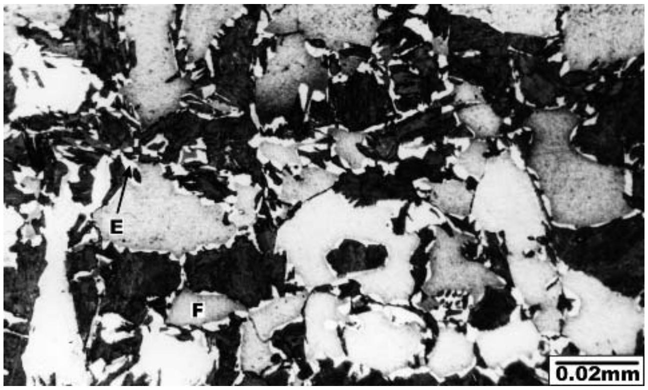

Fig. 1 Microstructure of dual-phase steel after intercritical annealing at 780 °C and then quenching in hot water shows the effect of alkaline chromate etch. M = martensite, F = old ferrite, and E = epitaxial ferrite

---

M. Sarwar, PAEC Dera Ghazi Khan, Pakistan; **R. Priestner,** Manchester Materials Science Center, Manchester, England; and **E. Ahmad,** PINSTECT, Nilore, Islamabad, Pakistan. Contact e-mail: drmsrana@yahoo.com.

Table 1 Fatigue Properties

Specimen Code	Percent Volume Fraction of Martensite	Ferrite Grain Size (μm)	Fatigue Limit (MPa)	Ratio of Fatigue Limit and UTS	Ratio of Fatigue Limit and 0.2% Proof Stress
OBQ780	55.0	19.5	395	0.427	0.63
50BQ780	48.9	9.8	428	0.40	0.63
QHWQ780	27	32.9	315	0.447	0.87
50OQ780	32	7.3	305	0.439	0.83
0BQ740	30.7	29.5	380	0.455	0.84
50BQ740	29.4	18.3	400	0.448	0.76
C(a)	32.0	…	378	0.413	0.91
E(a)	27	…	318	0.422	1.03
N_2 770(a)	42	…	383	0.413	0.80
Q 765(b)	32	…	344	0.392	0.75
N_1 765(b)	38	…	384	0.402	0.80

(a) These results are taken from Ref. 10.
(b) These results are taken from Ref. 11.

tric circles having diameters of 79.58, 53.05, and 26.53 mm, adding up to a total line length of 500 mm, were superimposed on photographic prints of the microstructure and the number of intercepts of the circle with ferrite grains were counted. The main linear intercept in the ferrite d_α was calculated according to the relationship given in Ref. 4.

A suitable magnification was used to obtain about 140 intercepts per field per phase. A total of about 550 to 650 intercepts were counted to get reasonable statistical accuracy.

2.3 Fatigue Limit Tests

Fatigue tests were performed on an Avery 7303 machine (United Kingdom) which operated in reverse plane bending at a fixed frequency of 1420 cycles/min. A series of stress values was used to establish an approximate signal to noise (S/N) curve, and then subsequent specimens were tested at stresses that gave fatigue lives of about 10^7 cycles. Tests were conducted at a load ratio of $R = 0$, (where $R = \sigma_{\min}/\sigma_{\max}$).

The machine was used for reversed plane bending at constant amplitude. The vertical displacement of the bending arms was measured with a dial gauge, and the bending moment was obtained from a calibration graph, which related these two variables. A wide range of stresses can be applied to specimens by using springs of different stiffness.

3. Results and Discussion

3.1 Effect of Microstructure on Fatigue Limit

Different intercritical heats and thermomechanical treatments were selected to study the effect of volume fraction of martensite, grain size of ferrite, and contents of epitaxial ferrite on fatigue limit. Figure 1 indicates the microstructure of dual-phase steel after intercritical annealing at 780 °C and quenching in hot water. To distinguish between old ferrite and epitaxial ferrite (new ferrite), an etching technique developed by Lawson et al.[5] was used. This etching technique revealed epitaxial ferrite as white, old ferrite as gray, and other constituents as black area, as shown in Fig. 1. The arrow in the white area indicates epitaxial ferrite, the letter ‘F’ in the gray area indicates old ferrite, and the letter ‘M’ in the black area indicates martensite. Note that the different processing steps required to provide these comparisons also vary the apparent ferrite grain size, the mean linear path in ferrite between martensite particles, and the substructure in ferrite. Specimens of each of the microstructure series were tested on an inverse plane bending fatigue machine. The results are listed in Table 1, in which the specimens are coded according to heat treatment given. Figures 2 and 3 illustrate the effect of martensite contents on fatigue resistance for rolled and not rolled material. It can be seen that, with increasing martensite content, the fatigue limit improved.

Figure 4 shows the effect of warm rolling at an approximately constant volume fraction of martensite. The warm rolling at 780 °C increased the fatigue limit. Similar behavior was also observed as a result of warm rolling at 740 °C.

The effect of epitaxial ferrite on fatigue limit was also considered. Figure 5 shows that material quenched in hot water from 780 °C (not rolled) had a lower fatigue limit than the material quenched in brine from 740 °C. Both contained approximately the same volume fraction of martensite, but the former also contained approximately 20% of epitaxial ferrite. Similar behavior was also observed as a result of warm rolling, i.e., epitaxial ferrite reduced the fatigue limit.

Studies of dislocation substructures in as-produced dual-phase steel[6] have revealed higher dislocation densities in the ferrite phase compared with that found in polycrystalline iron. In addition, the dislocation density is nonhomogeneous and reaches a maximum near the martensite boundaries. This increase in dislocation density can be attributed to the martensite transformation shear and to the volume expansion of about 4% during martensite formation. In fact, this cell structure is like that found in cyclically deformed high strength low alloy (HSLA) steel.

Deformation in the ($\alpha + \gamma$) two-phase region produces a substructure in deformed ferrite.[7] The formation of substructure in ferrite during warm rolling is shown in Fig. 6. As shown in Table 1, specimens 50BQ780 and 50BQ740 exhibited higher fatigue limit compared to specimens 0BQ780 and 0BQ740 with the same volume fraction of martensite. Either fibering of martensite or the substructure produced during rolling in the two-phase ($\alpha + \gamma$) region may have contributed to improve the fatigue limit. It was also observed that the substructure formed

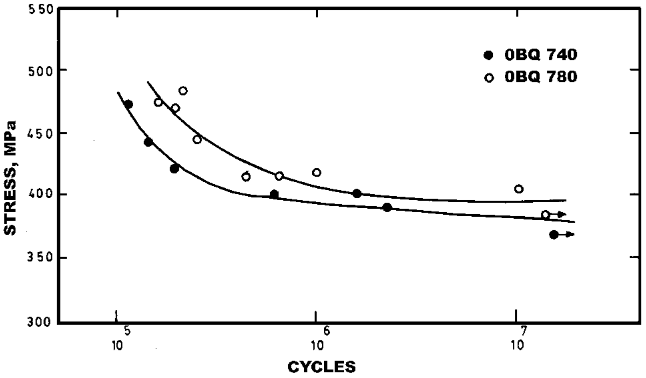

Fig. 2 Effect of martensite content on S/N curve, specimens 0BQ780 and 0BQ740

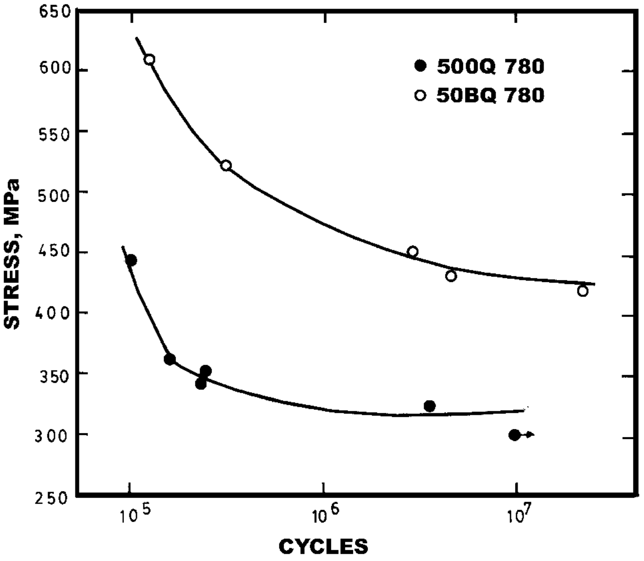

Fig. 3 Effect of martensite content on S/N curve, specimens 50BQ780 and 50OQ780

in ferrite in the specimen that was intercritically annealed at 780 °C then rolled to 48% reduction before oil quenching.[8,9] This specimen showed a marked decrease in fatigue limit, and in this case the formation of substructure in old ferrite and substructure-free epitaxial ferrite may have compensated for each other to achieve the lowering of the fatigue limit relative to specimens 50BQ780 and 50BQ740. The presence of approximately 20% epitaxial ferrite in the specimen quenched in hot water from 780 °C also exhibited a lower fatigue limit compared with the specimen 0BQ740, which had the same volume fraction of martensite but was free from epitaxial ferrite.

Cai et al.[10] studied a 0.11 C, 1.6% Mn, 0.73% Si steel containing different microstructures produced by a careful heat treatment, such that the volume fraction of the martensite was constant at 30%. The fatigue limits for material containing lath martensite before intercritical annealing (C) and material cooled from the austenite phase field to the intercritical annealing temperature (E) are listed in Table 1. Figures 7 and 8 contain data from Cai et al.[10,11] together with data from the present study. Clearly, the data from all sources show a common dependence of fatigue limit on volume fraction of martensite.

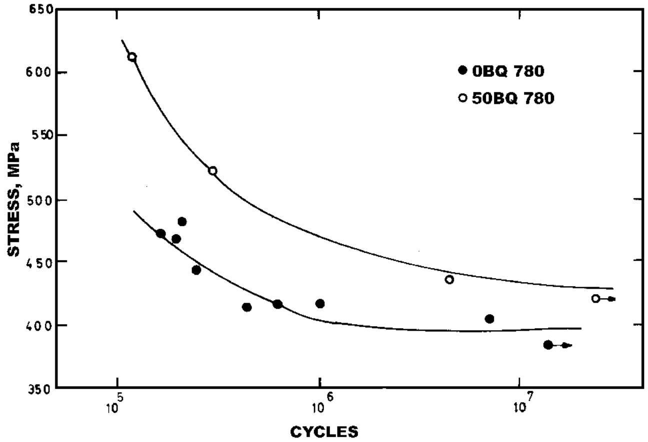

Fig. 4 Effect of microstructure on S/N curve, specimens 0BQ780 and 50BQ780

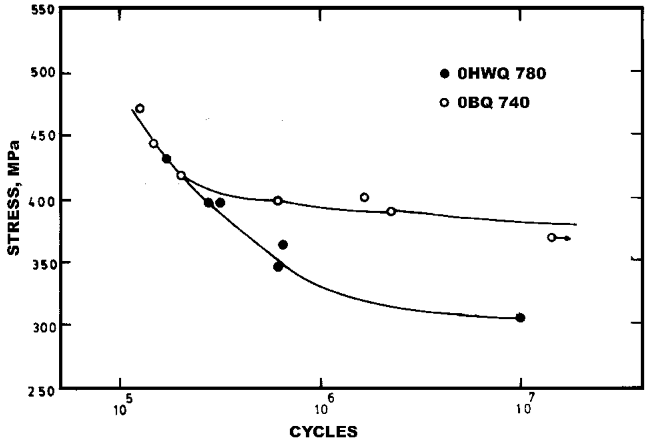

Fig. 5 Effect of epitaxial ferrite content on S/N curve, specimens 0HWQ780 and 0BQ740

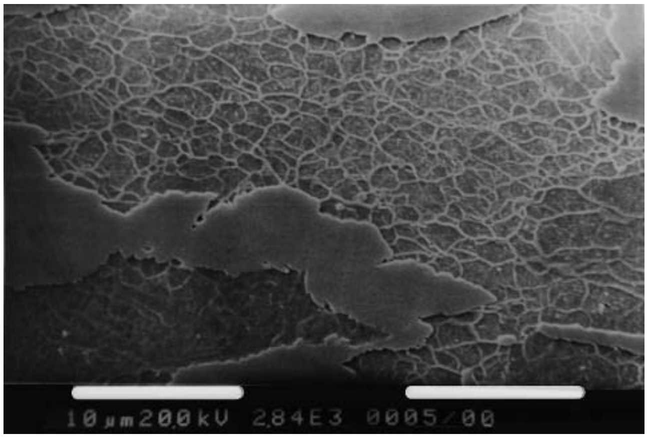

Fig. 6 Scanning electron micrograph showing the substructure formation in ferrite during rolling, specimen 50BQ740

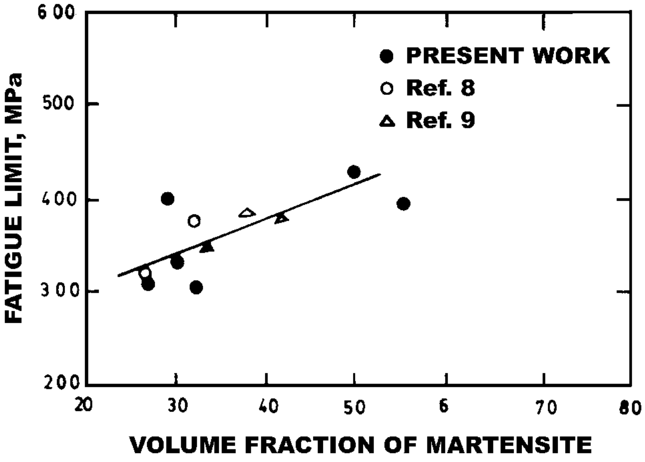

Fig. 7 Effect of martensite content on fatigue limit

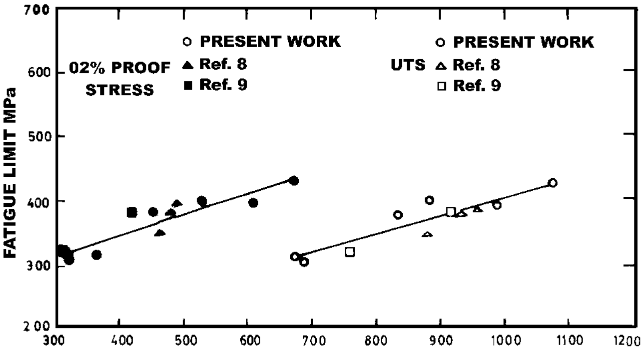

Fig. 8 Variation of fatigue limit with strength, MP

The ratio of fatigue limit to ultimate tensile strength (UTS) (Table 1) is close to 0.4 for all specimens. This is approximately the ratio commonly found in high-strength structural steel. In contrast, the ratio between the fatigue limit and 0.2% proof stress is more variable, ranging from 0.63 to 0.87. The ratio of fatigue limit to UTS for both specimens studied by Cai et al. was similar to those observed in the present work.

The ratio of fatigue limit to 0.2% proof stress was close to unity.

Figure 9 shows variation of the fatigue limit, 0.2% proof stress, and UTS with ferrite grain size. Fatigue limit and strength increased with the decrease of ferrite grain size.

The above discussion showed that the formation of substructure in ferrite and refinement of ferrite grains during warm rolling may be the main cause of improved UTS, 0.2% proof stress, and fatigue limit for rolled material. The presence of epitaxial ferrite for both rolled and not rolled material may be the reason for reduction in the strength and fatigue limit.

4. Conclusions

- Thermomechanical processing at the ICAT improved the fatigue limit, either by fibering of the martensite or as a result of the substructure produced during rolling.

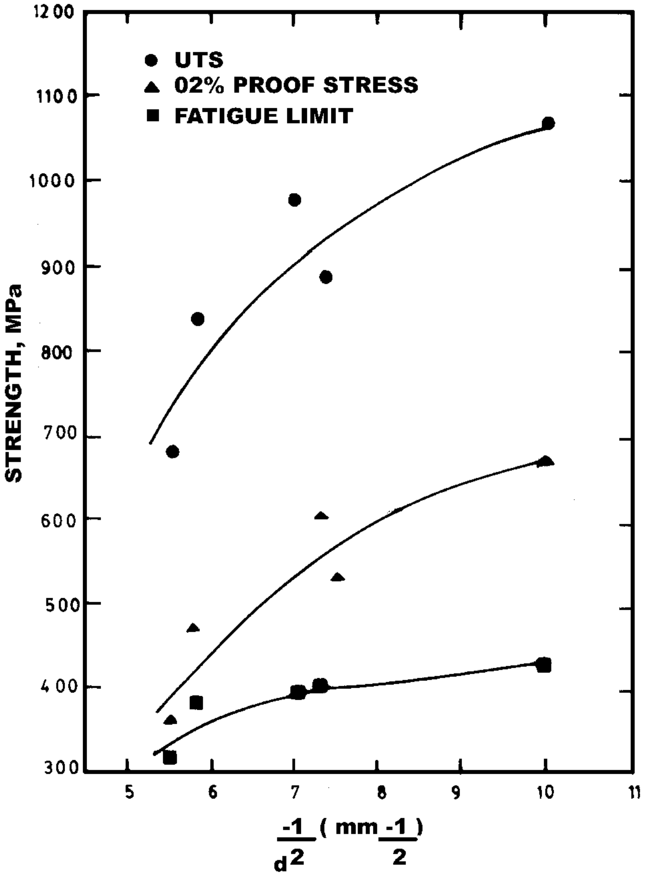

Fig. 9 Variation of fatigue limit and strength with ferrite grain size

- The material having approximately 20% epitaxial ferrite showed a reduction in the fatigue limit, and in this case the formation of substructure in old ferrite and substructure-free epitaxial ferrite may have compensated for each other to achieve the lower of the fatigue limit.
- A higher volume fraction of martensite improved the fatigue limit for both rolled and not rolled materials.

References

1. G.T. Eldis: "Structure and Properties of Dual-Phase Steels," in *AIME,* R.A. Kot and J.W. Morris, ed., 1979, pp. 202-05.
2. N.J. Kim: *Scr. Metall.,* 1984, *18,* pp. 817-20.
3. N.K. Balliger and T. Gladman: *Met. Sci.,* 1981, pp. 95-108.
4. F.G. Vander Vourt: "Practical Application of Quantitative Metallography," *ASTM,* 1984, *839,* pp. 85-131.
5. R. Lawson, D.K. Matlock, and G. Krauss: *Metallography,* 1980, *13,* pp. 71-78.
6. D.A. Korzekwa, D.K. Matlock, and G. Krauss: *Met. Trans. A,* 1984, *15A,* pp. 1221-28.
7. M. Sarwar and R. Priestner: *J. Mater. Sci.,* 1996, *31,* pp. 2091-95.
8. E. Ahmad and R. Priestner: *J. Mater. Eng. Perform.* 1998, *7*(6), pp. 772-76.
9. T. Tanaka: *Int. Met. Rev.,* 1985, *4,* p. 185.
10. Xue-Ling Cai, J. Feng, and W.S. Owen: *Met. Trans. A.,* 1985, *16A,* pp. 1405-15.
11. A.F. Aarezudar, M.Sc. Dissertation, Manchester Materials Science Center, UK, 1986, private communication, unpublished research.