FRACTURE AND FATIGUE CRACK GROWTH BEHAVIOR OF HIGH MARTENSITE DUAL-PHASE STEEL

Asim Bag *, K.K.Ray +, K.Aprameyan *, E.S.Dwarakadasa @ and K.V.Sudhakar◊

** Materials Science Lab., R&D Division, BEML, KGF - 563 115, India.*
+ Dept. of Metallurgical and Materials Engg, IIT, Khargapur-721 302, India.
@ Dept. of Metallurgy IISc., Bangalore-560 012, India.
◊Central Laboratory Foundry & Forge division, HAL, Bangalore-560 017, India.

KEYWORDS

Dual-Phase Steel, Ferritic-Martensitic Structure, Fatigue Crack Growth, Fracture Toughness.

ABSTRACT

Dual-phase microstructures with 33-78% martensite have been obtained by intermediate quenching of martensitic boron vanadium micro alloyed steel. The dependency of yield strength (YS) and ultimate tensile strength (UTS) on martensite content varied from predicted behaviour. Fatigue crack growth rates measured on half size compact-tension (CT) specimens indicated both increasing fatigue crackpath tortuosity and Paris slope 'm' with increasing martensite content. As volume percentage of martensite increases the fracture mode changes from predominantly cleavage to predominantly dimpled. Metallographic examination provides evidence for crack growth in the ferrite phase although martensite is the load bearing phase. As the martensite content increases, the ferrite phase is constricted leading to extensive crack branching. The presence of a corrosive medium results in crack blunting and increased resistance to crack growth, but fracture toughness drops significantly. Fracture surfaces increasingly become shallow, while still maintaining a close resemblance to the underlying microstructure. Quantitative values of tensile, fracture and fatigue properties are indicative of the high potential for the use of the dual-phase steel, containing 50-60% martensite in engineering applications.

INTRODUCTION

Conventional steels contain a distribution of lamellar or globular cementite in a ferritic matrix and exhibit a sharp yield point. In recent years, it has been shown that composite microstructures with varying quantities of martensite in ferrite, along with small quantities of retained austenite and/or bainite may be produced in what are called dual-phase (DP) steels. These steels exhibit a superior combination of strength and ductility, continuous yielding and a high work hardening rate related to several HSLA steels of similar chemistry. The ductility and formability characteristics of DP steels have been exploited by the sheet metal industry but it has yet to be used for components of thicker sections.

The evolution of DP steels has been critically reviewed by Rashid (1978), Davies (1978 a, b) and Repas (1987) concerning the role of chemistry and microstructural variables on their tensile and formability characteristics. It is now established that the microstructural parameters of significance are volume fraction of the two phases, size and distribution of martensite (Davies 1978a,b) and the size and morphology of ferrite (Lagneborg 1978, Marder 1981, Tanaka et al. 1979 and Chang and Preban 1985). Work so far has been limited to structures containing up to 25 % martensite. Although strength gradually increased, ductility and impact toughness decreased rapidly beyond such martensite contents (Kang and Kwon, 1987). There have not been any attempts to improve ductility and fracture resistance of steels containing more than 25% martensite. One possible reason for deterioration of properties in DP steels could be the morphology and hence any attempt to utilize a larger volume percentage of martensite (VPM) in the steel must focus attention on this. Accordingly this investigation examines the possible influence of microstructures in a series of suitably processed high martensite dual-phase steels.

EXPERIMENTAL

Material: A commercial micro alloyed steel in the form of 14 mm thick hot rolled stock was selected for the study. The chemical composition of the steel used is as follows: C 0.16, Mn 1.32, S 0.022, P 0.013, Si 0.44, Cr 0.03, Mo 0.09, V 0.056, B 0.0019 and N 0.004.

Heat treatment: The route to produce DP microstructure was by quenching the steel from the intercritical temperature (α + γ) region of the Fe-C diagram, as in fig.1. Two methods are popular: a) The intermediate quench (IQ) and b) The step quench (SQ). It is interesting to note that the two routes yield entirely different types of distribution and morphology of ferrite and martensite.

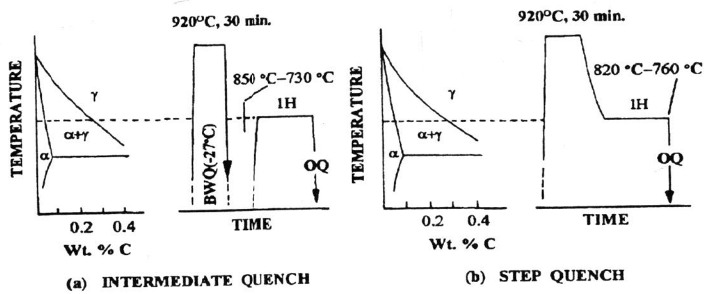

Fig.1 Schematic representation of heat treatment schedules for the (a)intermediate quench (IQ) and (b)step quench (SQ) treatments.

The IQ treatment consisted of soaking the specimens at 920°C for 30 min, quenching in iced brine, resoaking at different intercritical annealing temperatures (ICT) for 1h and then quenching in oil. The SQ treatment, on the other hand, consisted of austenitizing the steel at 920°C for 30 min., quenching to a temperature in the intercritical annealing zone, soak for 1h and then quench in oil. Specimens for all types of testing were heat treated in one batch for each variation of ICT for both IQ and SQ treatments.

Microstructural Characterization: After metallographic preparation and using a Leco image analyzer, the volume percentage of ferrite (VPF) and martensite (VPM), prior austenitic grain size (PAGS) and mean free path (MFP) of ferrite and martensite were determined. The amount of retained austenite was estimated by X- ray diffraction (XRD) analysis using a Philips X-ray diffractometer.

Impact tests: Impact test were carried out on standard Charpy V-notch specimens, as per ASTM specification E-23-86 at room temperature (25°C) using a standard pendulum type impact testing machine. A minimum of two specimens were tested for each heat treated microstructure.

Fatigue Crack Growth Test: Half size CT specimens milled out from larger sheets and then heat treated, were tested in load control mode on Instron 8032 servo hydraulic testing machine as per ASTM standard E647-93. All tests were conducted at 25 Hz sine wave and a load ratio of R=0.1 at room temperature (25°C) in (i) Laboratory air (RH=55%) and ii) in 3.5% NaCl. Crack growth rate was monitored using a traveling microscope on optically polished surfaces. In order to determine fatigue crack growth (FCG) threshold stress intensity (ΔK_{th}) values, all tests were started at an initial value of stress intensity factor (ΔK) = 20 MPa$\sqrt{m}$ and a load shedding procedure was followed in steps corresponding to 0.05 mm extension in crack length, keeping the load ratio constant (R=0.1). Tests were terminated when the physical value of crack growth became negligible even after one million cycles of stress. At least two specimens were tested for each microstructural state. In order to know the general corrosion behaviour, weight loss data during continuous immersion in 3.5% NaCl for a total period of 40h were also obtained.

Impact and fatigue fractured surfaces were examined in a JEOL model 840A scanning electron microscope for studying the nature of fracture.

RESULTS AND DISCUSSION

A typical set of dual-phase microstructures obtained by the IQ and SQ treatments are given in fig.2. In all cases the microstructures contained proeutectoid ferrite and transformed martensite. In view of the presence of ferrite, facilitating transformation of austenite the amount of retained austenite was just about 2-3%, as determined by XRD techniques. Microstructures obtained through IQ treatment were very similar to those reported by earlier workers (Davies 1978a,b and Repas 1987).

The percentage of martensite formed as a function of ICT for IQ and SQ treated DP steels are given in fig.3. The mean free paths in both ferrite and martensite for IQ treated steels are given in fig.4. For SQ treated steels MFP vary from 20-25μm across the banded direction and over 100 μm along the banded direction. It may be observed that the volume percentage of martensite could be changed from 33% to 78% by changing the annealing temperature of the IQ treatment. Microstructures obtained by SQ treated were very coarse and banded.

Further the impact test data revealed that the SQ treated structures exhibited very poor impact values (fig.5) despite having good YS and UTS values. For this reason the SQ product was not considered for FCG tests. The entire set of data and analysis of FCG test reported here is for the IQ treatments.

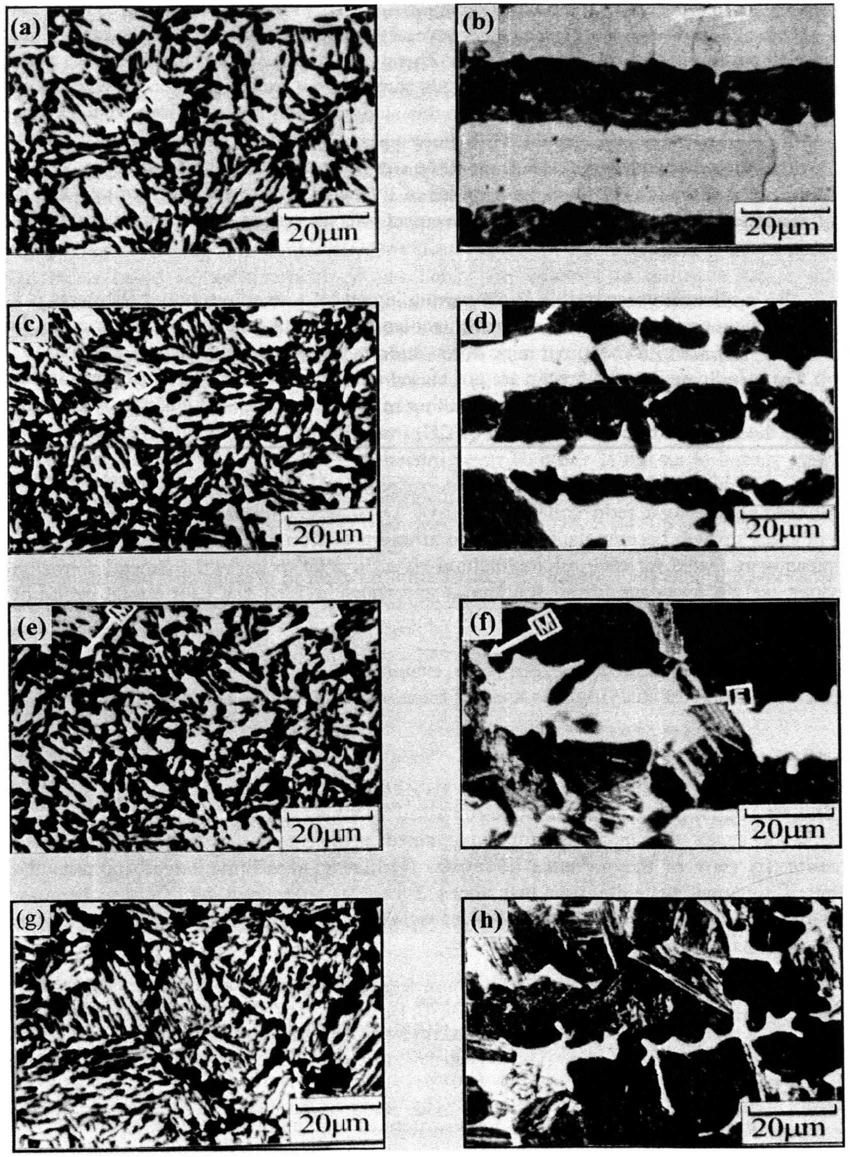

Fig.2 Typical optical micrographs of IQ (left column) and SQ (right column) treated specimens corresponding to ICT at (a,b) 760^{o}C , (c,d) 780^{o}C, (e,f) 800^{o}C and (g,,h) 820^{o}C.

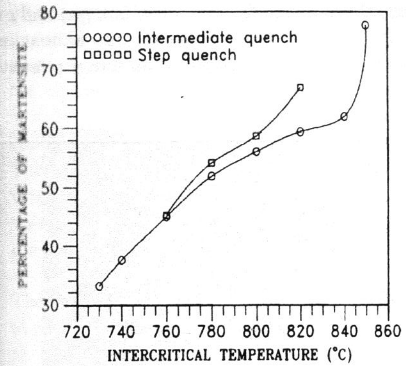

Fig.3 Volume percentage of martensite as a function of intercritical temperature of IQ and SQ treated dual-phase steels..

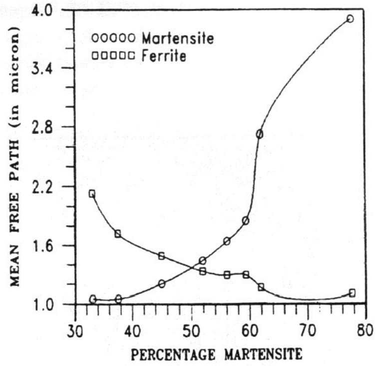

Fig.4 Change in mean free path with volume percentage of martensite for IQ treated dual-phase steels.

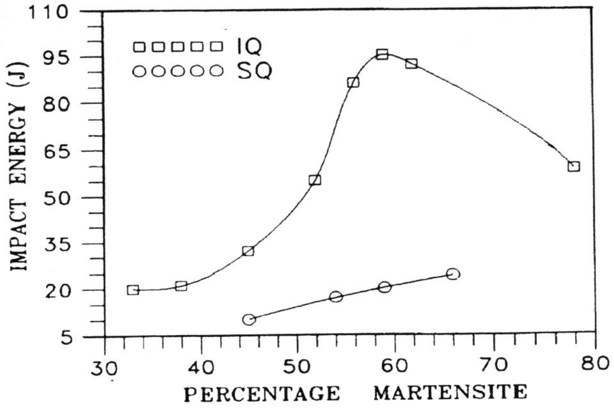

Fig.5 Charpy impact energy versus volume fraction of martensite in IQ and SQ treated dual-phase structures.

The effect of varying martensite content on the yield and tensile strengths of the dual-phase steel was reported separately (Bag,1996). The variation of strength with VPM indicated an unusual inflexion around 50% martensite which is dissimilar to the results reported by previous investigators (Davies 1978a, Marder 1981, Cheng 1985). Specimens exhibited significant necking before breaking. The fractured surfaces revealed only fibrous and shear lip zones; the absence of the radial zone indicates that crack initiation takes place from several points on the circumference and grow to join to form the fibrous zone to a size which leads to plane stress shear fracture of the rest of the ligament. Results were in agreement with the high uniform elongations of the developed DP steel.

Impact fractures of the DP steel exhibited predominantly cleavage for low VPM and gradually changed to predominantly dimpled for high VPM supporting the view that although martensite was the load bearing phase, the crack initiated and propagated in the ferrite phase. A set of typical fracatographs of impact fractured specimens is given in fig. 6.

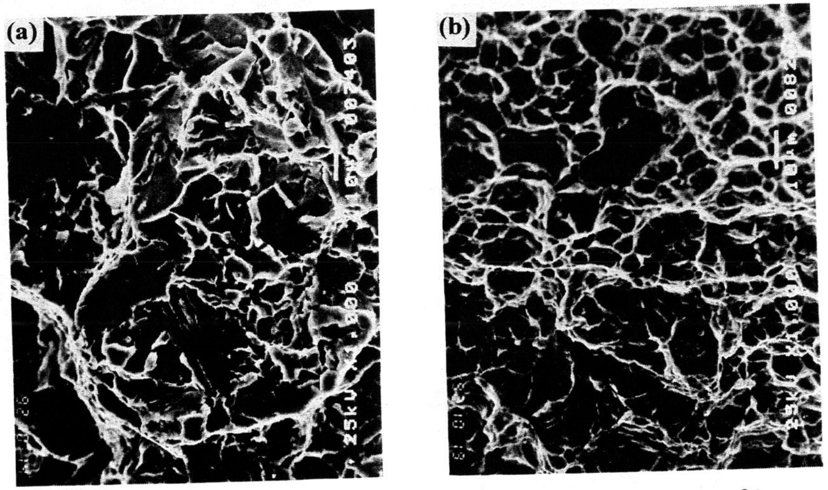

Fig.6 Typical SEM fractographs of DP steels corresponding to ICT at (a) 740°C and (b) 820°C.

From the observed values of crack growth at different ΔK values plots of da/dN Vs. ΔK were drawn for all the specimens as shown in fig.7. Values of ΔK_{th} and Paris constants 'C' and 'm' were evaluated. The magnitude of ΔK_{th} in air and 3.5% NaCl vary linearly with VPM as given in fig.8.

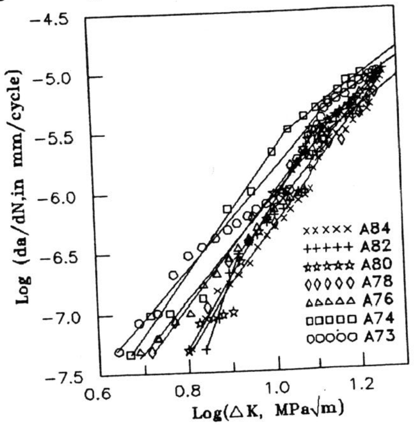

Fig.7 Variation in near threshold fatigue crack growth rates with nominal stress intensity range.

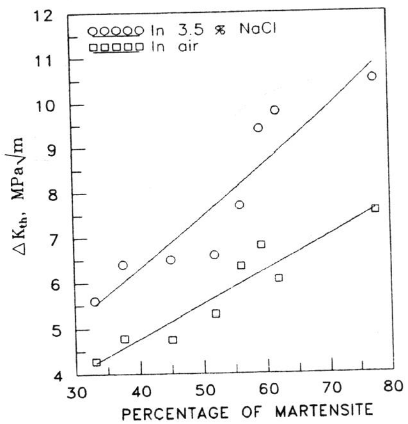

Fig.8 Variation of fatigue threshold with volume percentage of martensite.

The observed high strength and fine microstructures of the DP steels lead to some concern as to their FCG behaviour. Fortunately several investigators have reported superior ΔK_{th} values without sacrificing the strength levels. Zheng et al.(1994) contend that DP steels perhaps have the highest ambient temperature fatigue threshold for metallic materials without sacrificing strength. Observed values for ΔK_{th} in this study probably lie in the lower bound range of this contention, but are comparable with those reported for several commercial structural materials The linear dependence of ΔK_{th} on VPM can be expressed in the form: $\Delta K_{th} = a + b(VPM)$ where a and b are constants with values of 1.75 and 0.075 respectively when VPM is taken in volume %. This relation is not in agreement with the results of Chen et al.(1988) but follows the results suggested by Bullouch and Kennedy (1985).

The mechanism responsible for imparting higher ΔK_{th} to conventional DP steels is attributed to roughness induced crack closure effect leading to tortuous crack paths during FCG(Dutta et al. 1984). Careful metallographic observation in the regions immediately adjacent to the crack paths indicate that the cracks are not biased either by ferrite or martensite or interfaces in the microstructure. The nature of the crack paths (fig.9) also does not lead to any inference related to the crack path roughness effect on ΔK_{th} values simply by a qualitative examination.

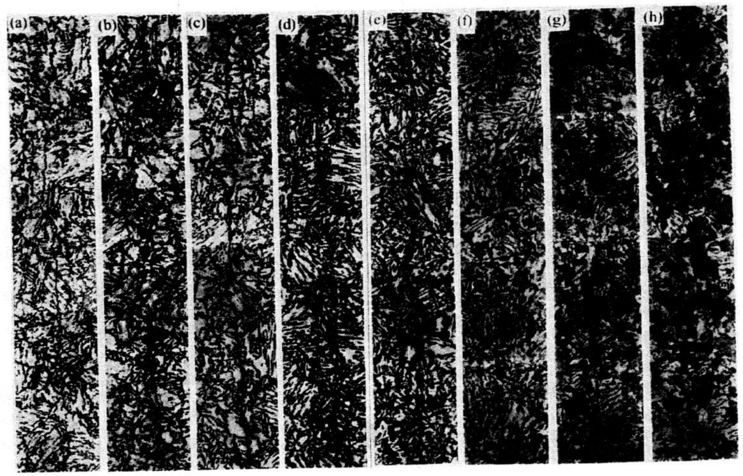

Fig.9 Crack paths formed near fatigue threshold region in different DP steels corresponding to ICT at (a) 730°C, (b) 740°C, (c) 760°C, (d) 780°C, (e) 800°C, (f) 820°C,(g) 840°C, and (h) 850°C.

CONCLUSIONS

Ferrito-martensitic dual phase microstructures containing up to 78% martensite obtained by step quenching and intercritical quenching treatments indicated that the latter treatment giving nearly equal amounts of ferrite and martensite results in the best combination of properties - strength, ductility and toughness.

2-3% retained austenite present in the DP structures do not seem to exert any influence on the mechanical properties.

Banding was absent and the martensite was a mixture of globular and plate type martensite for the IQ treatment.

The impact fracture toughness values of SQ treated specimens are much inferior when compared with those of IQ treated specimens and exhibit a peak between 50-60% martensite contained IQ treated DP steels. Magnitudes of fatigue thresholds lie between 4.19 and 7.5 MPa√m for tests in air and 5.6 - 10.5 in NaCl environment as VPM varies from 33 to 78%. These values are significantly lower than those for SQ treatment reported in literature and can be explained in terms of magnitudes of roughness induced crack closure.

The DP steel under investigation exhibited good general resistance to corrosion in 3.5% NaCl with values of 5.0 to 12.5 mm per year over a 100 h exposure.

In the presence of a corrodant, fatigue threshold values seem to improve slightly (5.6 to 10.50 MPa√m), but fracture toughness values decrease as expected. This is explained by the nature of general corrosion on the surface, but the exact mechanism is being worked out.

This investigation indicates that a combination of prior austenitic grain size of 11 μm, YS of 651-682 MPa, UTS = 844-928 MPa, impact fracture toughness of 54-100J and a fatigue threshold of 5.2-6.9 MPa√m for a steel containing nearly equal volume percentage of ferrite and martensite in the dual-phase steel seems to be superior to plain carbon steels and HSLA steels of similar chemistry.

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