TENSILE BEHAVIOR OF INTERCRITICALLY TREATED HIGH MARTENSITE DUAL-PHASE STEEL

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KEYWORDS

Dual-Phase Steel, Ferritic-Martensitic Structure, Tensile, Fracture, Step Quench, Intercritical Quench, Intermediate Quench.

ABSTRACT

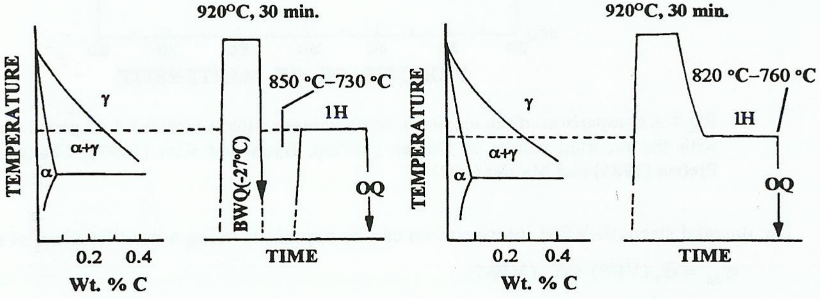
Dual-phase microstructures with varying contents of martensite were prepared by intermediate quenching (IQ) of initial martensitic microstructures of a boron-vanadium containing micro alloyed steel. Subsequently, these steels with ferrite-martensite microstructures were then investigated in order to understand their tensile behaviour. Quantitative microstructure characterization of the dual-phase steels were also carried out to correlate the microstructure with the tensile behaviour. The role of the microstructure was assessed using plots of the tensile parameters vs. corresponding volume percentage of martensite (VPM). The nature of the variation of tensile parameters for IQ treated dual-phase steels with VPM is significantly different from those reported in the literature. Best optimised properties are exhibited by dual-phase steels with equal amounts of ferrite and martensite. This unusual tensile behaviour has been explained using a model which considers the strength of ferrite and martensite as the dependent on the microstructural morphology.

INTRODUCTION

In the recent past it has been shown that composite microstructures of varying quantities of martensite in ferrite, with small quantities of retained austenite and/or bainite, called dual-phase (DP) steels exhibit a superior combination of strength and ductility, continuous yielding and a high work hardening rate relative to several HSLA steels of similar chemistry. The ductility and formability characteristics of DP steels have been exploited by the sheet metal industry but has yet to be established for components of thicker sections. 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).

The understanding gained on the various structure-property relationships of DP steels over the last three decades is limited to microstructures containing upto 25% martensite. The major cause for this limitation is the fact that though strength gradually increases, ductility and impact toughness of DP steels degrade rapidly beyond such a level of martensite (Kang and Kwon 1987).

Two types of heat treatment schedules are popular for obtaining ferrite-martensite microstructures: (a) intermediate quench (IQ) and (b) step quench (SQ). The schematic representation of both heat treatments are shown in fig.1. It has been shown (Bag 1996) that an IQ treatment yields finer microstructures and hence better impact properties than SQ treated microstructures. Therefore, the aim of the present investigation is to examine the tensile behaviour of a series of high martensite (33 to 62 %) dual-phase steels developed via the IQ route.



(a) INTERMEDIATE QUENCH **(b) STEP QUENCH**

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

EXPERIMENTAL:

Material: Micro alloyed steel in the form of 14 mm thick hot rolled stock was selected for this study. The composition of the material was determined using a Baird optical emission spectrometer, together with a Leco carbon-sulphur and Leco oxygen-nitrogen determinator, and is given in Table 1.

Table 1 Chemical Composition of the Steel

ELEMENTS	C	Mn	S	P	Si	Cr	Mo	V	B	N
Wt.%	0.16	1.32	0.002	0.013	0.44	0.03	0.09	0.056	0.0019	0.004

Heat treatment: 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.

Microstructural characterization: Several stereological measurements were carried out to estimate (a) the volume percentage of ferrite (VPF) and martensite (VPM) in the developed microstructures using a manual point counting technique and by automatic analysis using a Leco image analyzer, (b) the prior austenite grain size (PAGS) using the random intercept method, and (c) mean free path (MFP) of ferrite and martensite by lineal analysis (UnderWood 1970). The amount of retained austenite was estimated by X-ray diffraction analysis using a Philips X-ray diffractometer.

Tensile tests: Tensile tests were carried out on round specimens having diameters of 8.75 mm with gauge lengths of 60 mm. The specimens were tested using a servo-hydraulic Universal Testing Machine (Instron-8032). All tests were conducted at room temperature using nominal strain rates of 1×10^{-3}/sec. The fractured surfaces of the broken tensile specimens were examined in a scanning electron microscope (JEOL model 840A) to determine the fracture morphology.

RESULTS AND DISCUSSION

The measured microstructural parameters are given in Table2. and a typical set of optical microstructures is given in fig.2. The microstructures obtained are very similar to those reported earlier (Davies 1978a,b and Repas 1987). The average values of PAGS was found to be 11.0±4.67 μm. The finer PAGS are considered suitable for developing dual-phase microstructures because these would lead to finer sizes of ferrite and martensite. The mean free path of ferrite and martensite are a minimum when the volume percentage of both phases are approximately equal. The dual-phase microstructure contain 2-3% retained austenite and some undissolved fine carbide. The latter constituent is found at lower ICTs upto 760°C for 1h. duration.

Table 2 Results of the quantitative microstructural analysis

Inter Critical Temp. (°C)	Specimen Code	Volume %			Mean Free Path (in μm)	
		Ferrite	Martensite	RA	Ferrite	Martensite
730	A73	66.90	33.10	—	2.13	1.05
740	A74	62.45	37.55	3.77	1.72	1.05
760	A76	54.95	45.05	2.17	1.49	1.20
780	A78	48.10	51.90	2.36	1.33	1.44
800	A80	43.96	56.04	3.50	1.29	1.64
820	A82	40.63	59.37	2.90	1.29	1.85
840	A84	38.09	61.91	—	1.16	2.72

Note: RA= Retained Austenite,"——" Not determined, RA% is included in % of Ferrite.

The strength (yield and tensile) and percentage elongation (uniform and total) for each microstructural state were determined from at least three specimens. The scatter associated with the individual values from the average for a specific VPM was found to be within 3%. The variations of average strength and percentage of elongation with VPM for each type of specimen are shown in fig.3. The variation of strength (both yield and tensile) with VPM indicated an unusual inflexion around 50% VPM (fig.4) which is dissimilar to the results reported by previous investigators.

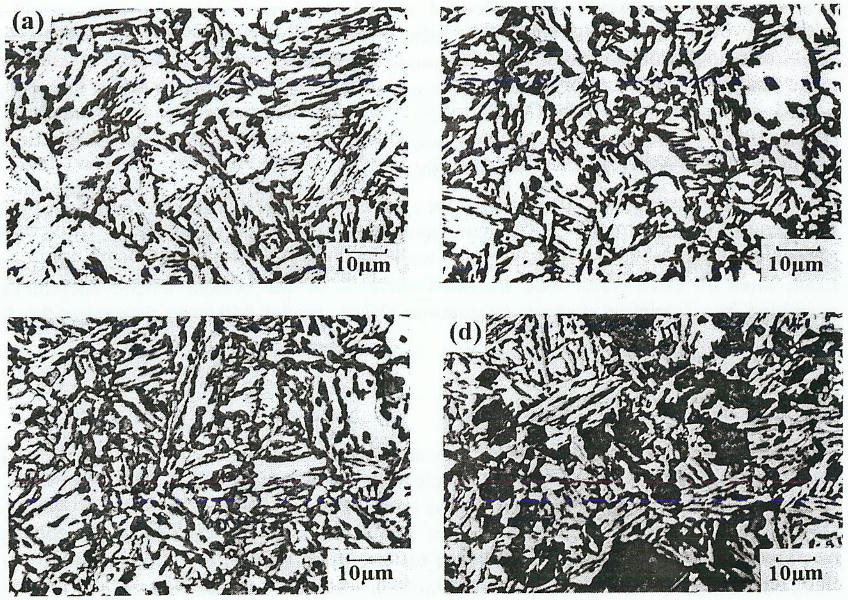


Fig.2 Typical optical micrographs corresponding to ICT at (a) 730°C , (b) 760°C, (c) 800°C and (d) 840°C.

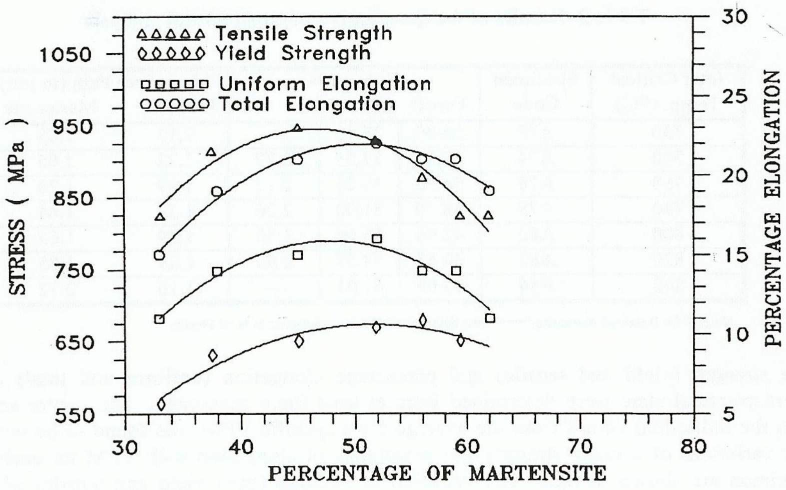


Fig.3 Different tensile parameters as a function of volume percentage of martensite.

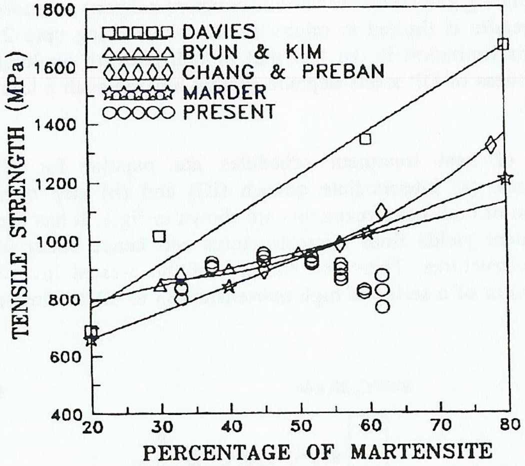


Fig.4 A comparison of the tensile strength values of the IQ treated dual-phase steels with the reported results of Davies (1978a), Byun and Kim (1993), Chang and Preban (1985) and Marder (1981).

The unusual strength-VPM inter-relation can be explained using a modified law of mixtures:

$$\sigma_{dp} = \overline{\sigma}_f(VPF) + \overline{\sigma}_m(VPM) \qquad ...(1)$$

where, VPF=Volume percentage of ferrite, VPM=Volume fraction of martensite, $\overline{\sigma}_f$ =average strength of ferrite, and $\overline{\sigma}_m$ =average strength of martensite.

The average strength of ferrite was considered to depend on the mean free path of ferrite(d_f):

$$\overline{\sigma}_f = \sigma_{of} + K_f d_f^{-1/2} \qquad ...(2)$$

Where σ_{of} and K_f are Hall -Petch constants.

The strength of martensite, on the other hand, was considered to be a cubic function of the inverse of the mean free path (d_m):

$$\overline{\sigma}_m = A + Bd_m^{-1} + Cd_m^{-2} + Dd_m^{-3} \qquad ...(3)$$

Where A, B, C, and D are constants.

The experimental and the calculated values of tensile strength against VPM are shown in fig.5. The straight lines connect the values of tensile strength of ferrite, and dual-phase structures containing different volume percentage of martensite. This proposed model was found to be suitable for explaining all yield and tensile strength results of specimens containing different VPM; but this needed consideration of different values of the constants in eqn.(2) and eqn.(3) for computing yield and tensile strength values.

The work hardening behaviour of these materials was also studied using Hollomon (Davies 1978a, and Repas 1978) and Jaoul Crussard (Samuel 1987a, b) analysis. The Hollomon plot was found to be non-linear indicating that work hardening of these DP steels occurs in more than one stage. A series of alternate analyses, by plotting ln(dσ/dε) vs. lnε, fig.6, following

(Samuel 1987a, b) was carried out to demarcate the different stages of work-hardening behaviour of the microstructures. The plots indicate that the flow stress behaviour of the steel occurs in three stages.

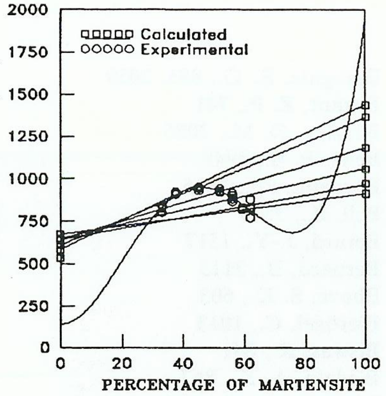


Fig.5 The experimental and the calculated values of tensile strength.

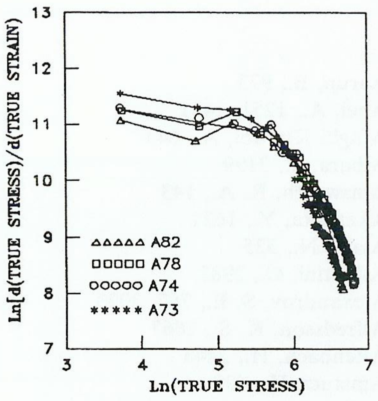


Fig.6 Modified Crussad-Jaoul plots of dσ/dε versus stress in logarithmic scale.

The tensile fracture surfaces observed with the scanning electron microscope exhibited a mixture of dimples and cleavages. It was found that the amount of cleavage fracture decreased upto approximately 50% VPM and then increased with further increase in VPM., fig.7.

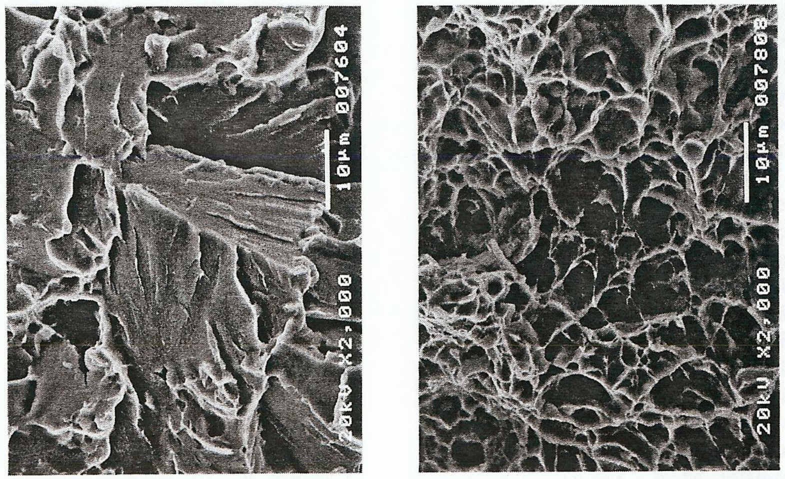


Fig.7 Representative fracture morphologies of predominantly cleavage facets (left) and predominantly dimple regions (right) in specimens containing 33% and 60% martensite respectively.

These observations indicate that the ductility of the material should be maximum at equal proportions of ferrite and martensite. Such observations can be explained due to the possibility of (i) void nucleation at carbide particle-matrix interfaces and at ferrite-martensite interfaces, and (ii) the influence of a micro-stress field originating from the distribution of the major phases on the voids which grow and coalesce.

CONCLUSIONS

The following conclusions can be derived from the work presented in this report:

Samples of dual-phase steels developed through IQ treatment, containing approximately equal amounts of ferrite and martensite exhibit the best optimized conditions of high strength with high ductility.

The effect of the variation of VPM on tensile and yield strengths of the developed DP steels have been explained with a new model which considers strength of ferrite and martensite to be dependent on the microstructural states.

The work-hardening exponent (n) calculated by using a conventional Hollomon's equation differs significantly from the uniform elongation obtained from true stress-true strain curves. This deviation emerges from the presence of different work-hardening rates during plastic deformation of the developed DP microstructures.

All the developed microstructures exhibit three stages of work-hardening

The micro-fractographs exhibit predominantly cleavage fracture for specimens containing lower VPM, and dimples for specimens containing higher VPM. Crack-initiation in specimens containing low VPM are stress-controlled whereas those in specimens containing higher VPM are strain controlled.

The peak in ductility in terms of percentage uniform elongation corresponds to the predominantly larger dimples observed in the fractographs for specimens containing approximately equal amounts of ferrite and martensite.

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