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Effect of Microvoid Formation on the Tensile Properties of Dual-Phase Steel

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A steel containing 0.32 wt.% C, 0.88 wt.% Mn, 0.99 wt.% Si, 0.9 wt.% Ni, and 0.9 wt.% Cr was intercritically annealed at different temperatures from 775 to 870 °C and quenched in oil to produce dual-phase steel microstructure. Tensile testing of these samples gave a series of strengths and ductilities. The tensile strength increased with the increased annealing temperatures and the martensite percentage increased with a reduction in ductility. Microvoids were formed near the fracture surfaces. The morphology of the microvoids changed with the martensite percentage from decohesion of the martensite particles to the intergranular and transgranular cracks, which defined the ultimate fracture mode of the specimens. The change in the morphology of microvoids may be due to a high percentage of carbon in the steel, which produced stresses in the matrix (ferrite) during phase transformation.

Keywords dual-phase steel, intercritical heat treatment, microvoids

1. Introduction

Dual-phase steels constitute a family of high-strength low-alloy grade, with microstructure consisting mainly of a hard second phase (martensite) in a soft matrix of ferrite. These steels exhibit unique combinations of strength and ductility.[1,2] The strength of the dual-phase steels is proportional to the percentage of martensite[3,4,5] and also on the carbon content of the martensite.[6] In sheet steels, the maximum strain is the sum of uniform and nonuniform strain associated with necking. The strain in the necked region is associated with a complex phenomenon and is controlled by strain hardening, strain rate sensitivity, nucleation, growth, and coalescence of microvoids. The distribution of microvoids in the necked region controls the ultimate failure mode during plastic deformation.[7]

The nucleation of microvoids in dual-phase steels is associated with either nonmetallic inclusions[8,9] or with martensite particles.[2,10] The nucleation of microvoids due to martensite particles is associated with the decohesion at ferrite-martensite interfaces and fracture of martensite.[1,2]

The aim of the present studies is to examine systematically the changes in the morphologies of microvoids, during the course of deformation, by increasing the martensite percentage. The results are co-related with the failure modes of overall tensile properties of the dual-phase steel.

2. Experimental Procedure

2.1 Material

A Chinese-based low-alloy steel designated as 30CrMnSiA was used for the present studies. The chemical composition of the steel is given in the Table 1. The material was provided by Shanghai G. S. E. International Trading Corporation (China) in the form of hot-rolled plates. The microstructural studies revealed that it contained ferrite and pearlite. The grains were equiaxed and no rolling bands from previous treatment were observed.

2.2 Heat Treatment

The provided Ac_1 and Ac_3 temperatures are 759 and 860 °C, respectively, determined by computer calculation. The intercritical heat treatments were conducted between this temperature range at 775, 790, 810, 825, and 850 °C. One sample was also heat treated at 870 °C, in the austenite region, to get full martensite. All the samples were quenched in oil at room temperature. The austenite present at the intercritical temperatures was transformed into martensite after quenching in the oil, due to relatively high hardenability of the steel.

2.3 Tensile Testing

Tensile tests were performed on the heat-treated samples using a universal testing machine (Instron model 1342, U.K.) Tensile properties were calculated from load versus displacement plots.

2.4 Metallography

All the specimens were ground, polished, and then etched in 2% Nital solution. The optical microscope (Leica, Wetzla, Germany), equipped with point counting accessories, was used for microstructural observation and quantitative metallography of ferrite and martensite. A scanning electron microscope (Leo,

Table 1 Chemical composition of the steel in wt. %

C	Mn	Si	Cr	Ni	Cu	S	P	Fe
0.32	0.88	0.9	0.91	0.09	0.08	0.07	0.02	Balance

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Cambridge, U.K.) was used to examine the microvoids near the fracture surface and fractrography of the ruptured tensile specimens.

3. Results and Discussion

3.1 Effect of Intercritical Heat Treatments on the Volume Fraction of Martensite

The variation of volume fraction of martensite with the intercritical temperature is presented in Fig. 1. The volume fraction of martensite increased with the intercritical temperature. A similar trend has been observed by Ahmad and Priestner[11] in a plot of the volume fraction of austenite (instead of martensite) versus intercritical temperature for 0.09 wt.% C low alloy steel. They quenched the specimens in the iced brine solution at −5 °C, after intercritical heat treatment, to ensure 100% transformation of austenite to martensite. In the present studies, 100% of austenite has been transformed to martensite (if no retained austenite is left) even at slower cooling rate (quenched in oil) due to good hardenability of the steel; these results are comparable with those of Ahmad and Priestner. At any intercritical temperature, the volume fraction of austenite present in their steel was less than the volume fraction of martensite in the present studies. The major difference between the two steels is the carbon content, higher in the present case, which reduced the quenching power required to transform the austenite to martensite.

3.2 Tensile Properties

The tensile properties of heat-treated samples are shown in Table 2. The strength of the steel increased with the volume fraction of martensite at the expense of ductility. These trends are shown in Fig. 2. In dual-phase steels, the increase in the strength with the martensite was observed by many workers, both in rolled[2] and unrolled[6] conditions. The tensile data of these researchers is also included in Table 2, for comparison. Speich and Miller[6] measured the tensile properties of steels with different carbon content. The increase in the ultimate tensile strength (UTS) with the martensite content was less than that observed in the present studies, but the ductility showed a reverse trend. The present tensile data are comparable with that of rolled steel of Sarwar and Priestner.[2] This comparison shows that higher carbon content of the steel (and of martensite) used in the present studies has improved the UTS but has had a detrimental effect on the ductility.

3.3 Formation of Microvoids and Fractrography

The microstructural studies in the necked region of the fractured tensile specimens showed that microvoids were formed

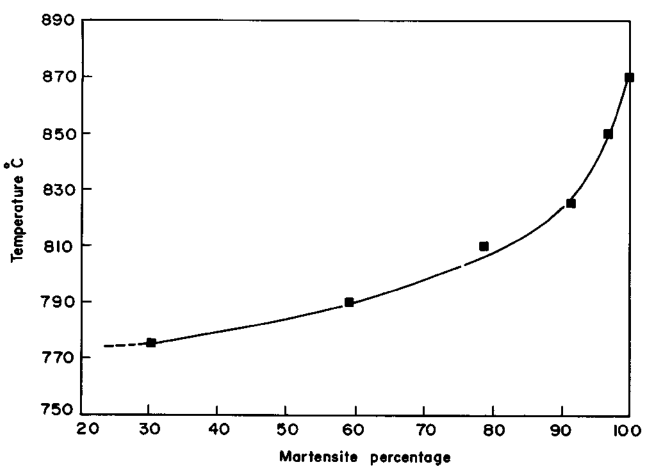


Fig. 1 Dependence of martensite volume fraction on annealing temperature

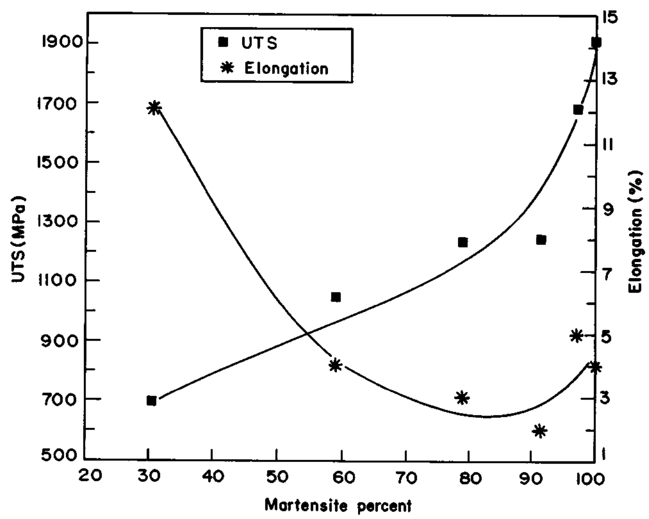
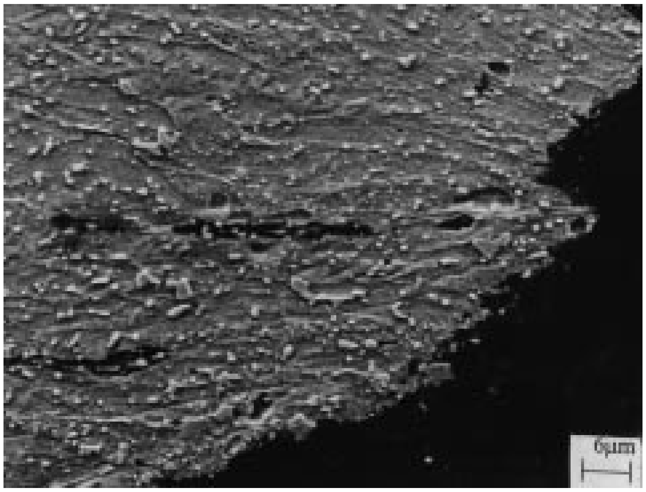


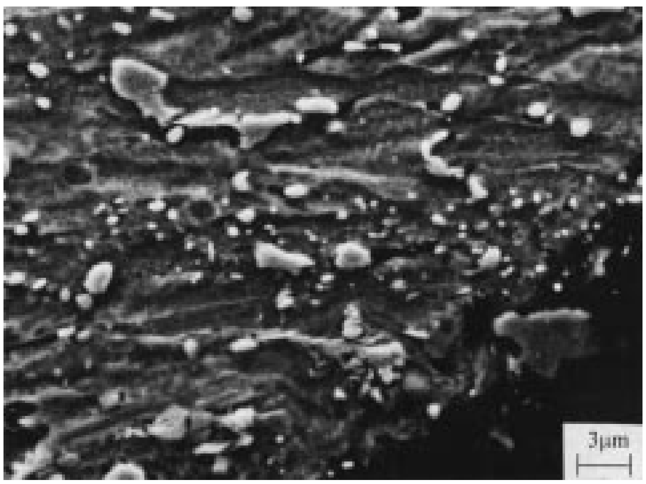
Fig. 2 Effect of martensite percentage on UTS and elongation (%)

Table 2 Heat treatment and mechanical properties of 30CrMnSiA low alloy steel

Specimen code	Heat treatment temperature, °C	Martensite volume, %	Yield stress (MPa)	UTS (MPa)	Elongation, %
INT-1	775	30.5	337	695	12
INT-2	790	59	622	1050	4
INT-3	810	78.8	506	1239	3
INT-4	825	91.4	497	1247	2
INT-5	850	97	540	1685	5
INT-6	870	100	630	1914	4
Ref 2	···	48.9	···	1069	8.9
Ref 6	···	50.3	···	920	10.2



(a)



(b)

Fig. 3 Formation of microvoids near the fracture surface in INT-1 specimen (**a**) at low magnification and (**b**) at high magnification

near the fractured surface. These microvoids were formed by decohesion at the interface and by fracture of the martensite particles in the INT-1 specimen, as shown in Fig. 3(a) and (b). The microstructure is also elongated along the tensile axis of the specimen. This shows that both ferrite and martensite deformed plastically before the catastrophic failure, resulting in the ductile mode of fracture (Fig. 4). At higher martensite percentage, the morphology of microvoids suddenly changed from decohesion at the interface to the microcracks, and fracture of martensite and ferrite, observed in INT-2 to INT-4 specimens (Fig. 5 to 7). These microcracks are approximately at right angle to the tensile axis, with minimum plastic deformation, resulting in a brittle type of failures (Fig. 8 to 10). The microcracks also formed, with some decohesions (Fig. 11 and 12), resulting in the mixed failure mode (Fig. 13 and 14), observed in specimens with higher martensite percentages (INT-5 and INT-6). The tensile deformation with the formation of microvoids, by decohesion of ferrite-martensite interfaces and fracture of martensite, has been observed by many authors in dual-phase

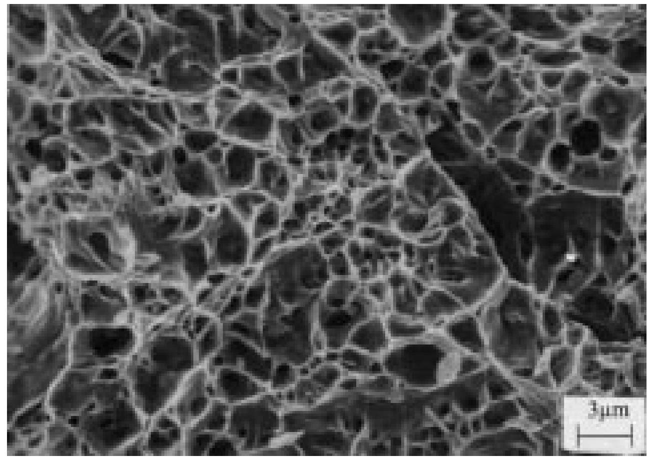


Fig. 4 Ductile dimples formed at the fracture surface of the INT-1 specimen

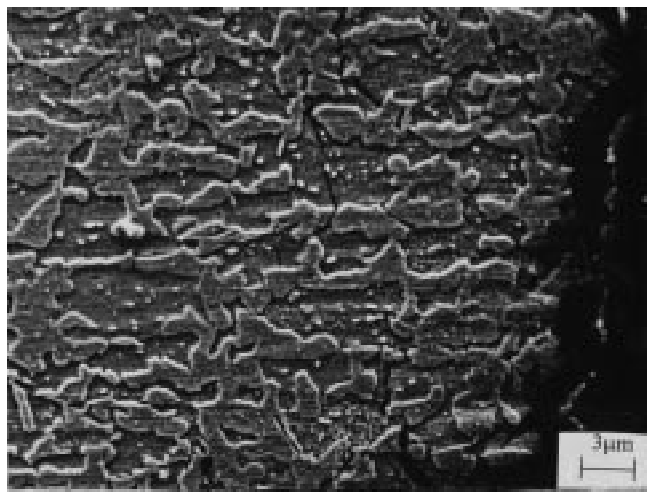


Fig. 5 Formation of microcracks near the fracture surface of the INT-2 specimen

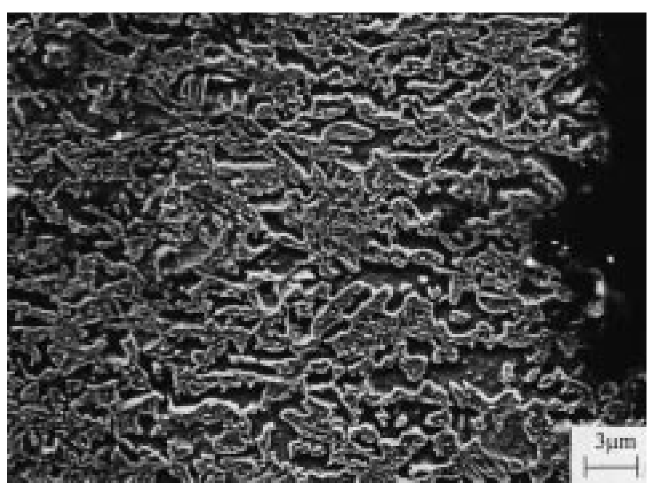


Fig. 6 Microstructure near the fracture surface of the INT-3 specimen

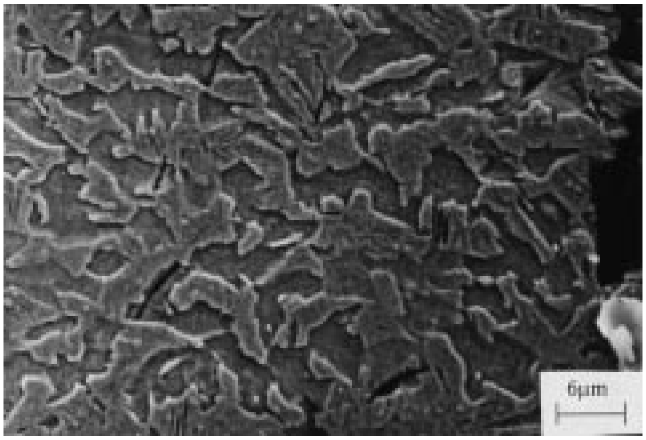


Fig. 7 Formation of microcracks near the fracture surface of the INT-4 specimen

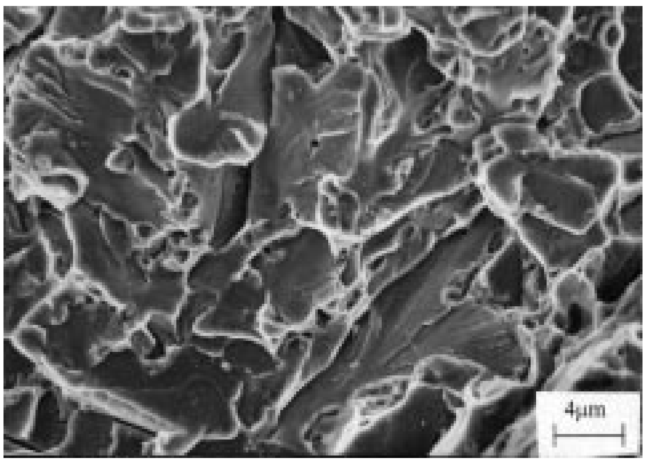


Fig. 8 Cleavage facets at the fracture surface of the INT-2 specimen

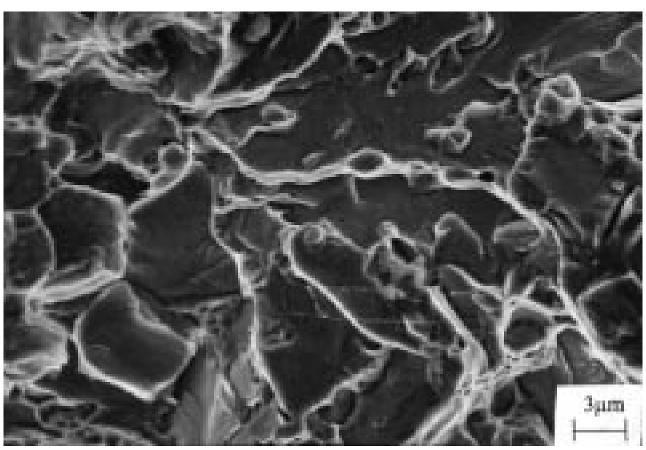


Fig. 9 Cleavage facets at the fracture surface of the INT-3 specimen

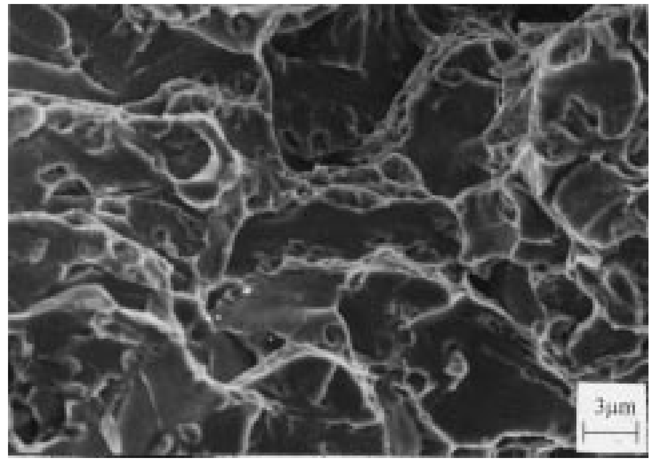


Fig. 10 Cleavage facets with few ductile dimples at the fracture surface of the INT-4 specimen

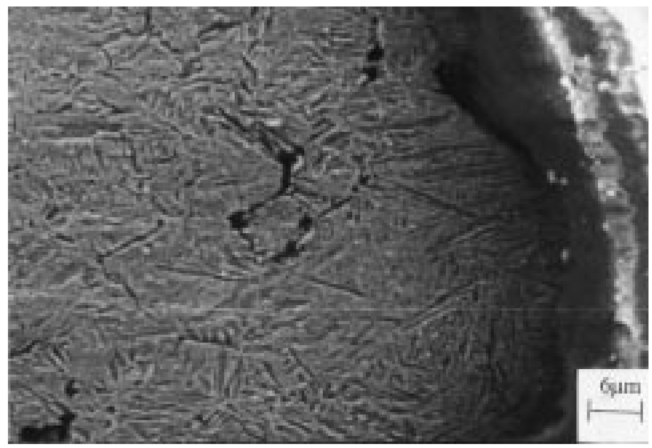


Fig. 11 Formation of microcracks in the INT-5 specimen

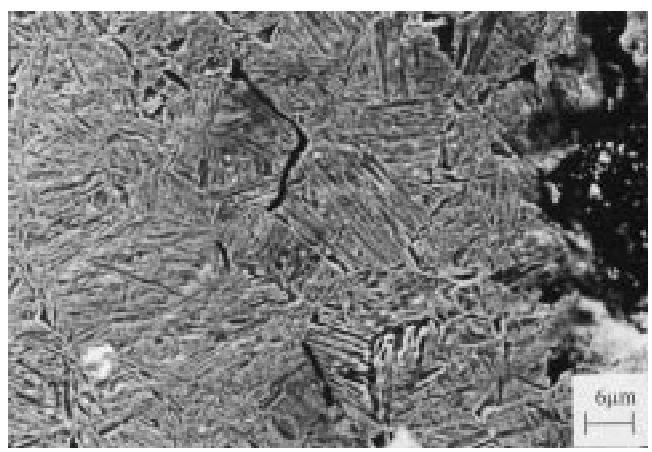


Fig. 12 Formation of microcracks in the INT-6 specimen

steels.[1,2,10] Another mechanism uniquely identified was decohesion at the interfaces with minimum plastic deformation, and microvoids appeared as microcracks that oriented at right angle to the tensile axes. These microcracks appeared only when martensite percentage increased from a limiting value (30.5%) in INT-1 specimen. The martensite transformation gen-

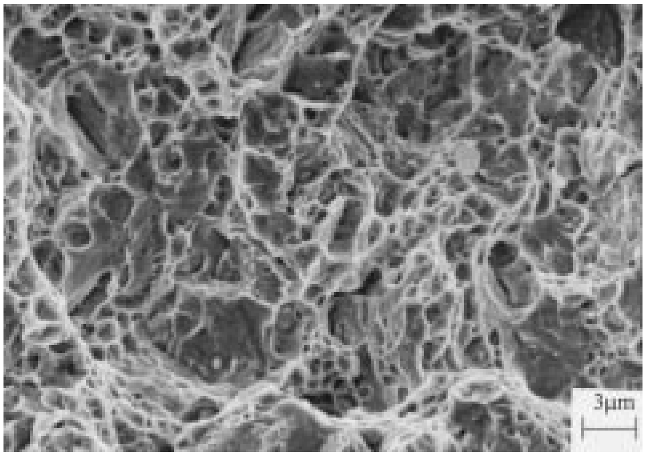


Fig. 13 Mixed mode of fracture with ductile dimples and a few cleavage facets in the INT-5 specimen

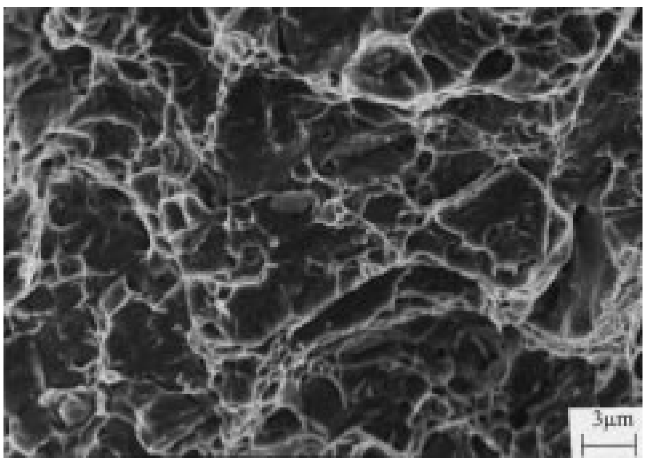


Fig. 14 Mixed mode of fracture with ductile dimples and cleavage facets in the INT-6 specimen

erates an abundance of new free dislocations in the ferrite matrix.[1] At higher martensite values (>30.5), as in INT-2 to INT-6 specimens, the effect of these dislocations would have been more pronounced, making the ferrite phase more difficult to deform in a brittle manner. Sarwar and Priestner[2] observed the plastic deformation of the ferrite and martensite in the necked region at 50% of martensite, while in the present studies, the INT-2 specimen at 59% of martensite showed minimum plastic deformation. This may be due to lower carbon content of Sarwar and Priestner's steel (0.17% C) than that of the steel used in the present studies, resulting in lower carbon content of the martensite. Higher carbon content of martensite, as in the present case, means that there is more carbon at the interstitial positions in the martensite, increasing its tetragonality. Therefore, due to the increased number of dislocations in the ferrite, brittle failure occurred.

Conclusions

- The heat treatment in the intercritical and full austenite region gave a series of ferrite and martensite combinations. The quantitative metallography results showed that ferrite and martensite at room temperature fell within the intercritical temperature range (759 to 860 °C), which means that austenite at any intercritical temperature fully transformed to martensite at a relatively slow cooling rate (oil quenching), which predicts the high hardenability of the steel.
- The tensile testing data showed that the strength of the steel increased with martensite percentage. This behavior of the material is in agreement with the previous work in the literature. However, the ductility decreased more rapidly then the strength increased.
- Microvoids were observed in the necked region of the ruptured tensile specimens. The morphology of these microvoids changed from decohesion at the interface to the microcracks, by increasing the martensite percentage. This may be due to high carbon content of the steel. The martensite transformation would have produced dislocations in the ferrite, resulting in low plastic deformation and poor ductility of the material at high martensite percentages.

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