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Effect of martensite strength on the tensile strength of dual phase steels

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Fe–2% Si–1.5% Mn steels with three levels of carbon content (0.10, 0.14 and 0.19 wt%) were intercritically annealed followed by water quenching to obtain dual phase (martensite plus ferrite) structure. It is found that the ultimate tensile strength of dual phase steels increased with increasing the volume fraction as well as the tensile strength of martensite. The tensile strength of dual phase steel can be predicted using the law of mixtures although the predicted tensile strength is slightly higher than the experimental one. It is suggested that martensite never reaches its ultimate tensile strength when the necking of dual phase steels occurs.

1. Introduction

Steels with microstructures composed of mixtures of ferrite and martensite are often called dual phase steels [1–5]. Both yield and ultimate tensile strength increase with increasing the volume fraction of martensite and can be estimated by the law of mixtures [1–5]

$$S_d = S_m V_m + S_f \cdot (1 - V_m) \qquad (1)$$

where S_d, S_m and S_f are the tensile strengths of the dual martensite and ferrite phases, respectively. V_m is the volume fraction of the martensite phase. Davies [6] has shown that both yield and ultimate tensile strength of dual phase steel depend only on the volume fraction of martensite but not on the carbon content of martensite. This is odd because the hardness of martensite, which can be correlated with the tensile strength, is strongly dependent on the carbon content [7, 8] and is expected to influence both yield and ultimate tensile strength of the dual phase steels. Contrary to the conclusion of Davies, Speich *et al.* [9] have reported that both yield and tensile strength of dual phase steel depend on the yield strength of martensite.

The present investigation had the objective of determining whether the tensile strength of martensite has an effect on the tensile strength of dual phase steel produced by intercritical annealing Fe–2% Si–1.5% Mn–C steels followed by water quenching.

2. Experimental procedures

The steels used in this investigation were melted in an argon gas atmosphere and cast into 6 kg ingots. The chemical compositions of the steels are shown in Table I, with Ac1 and Ac3 temperatures calculated from the empirical formula of Andrews [10]. The base composition was about 2% Si, 1.5% Mn and carbon was changed from 0.10% to 0.19%. The cast steels were soaked at 1250° C for 30 min, hot rolled to 2 mm in thickness at 950° C and air cooled.

The heat treatment consisted of intercritical annealing the steels for 10 min at various temperatures between the Ac1 and Ac3 temperatures followed by water quenching. The microstructures of steels were observed with an optical and transmission electron microscope. Volume fraction of martensite was determined by the point counting method. Tensile specimens with gauge length of 25 mm were tested using a 500 KN MTS servohydraulic machine at a cross head speed of 3 mm min^{-1}.

In order to simulate the tensile strength of the ferrite phase in the dual phase steels, diamond pyramid microhardness measurements with 5 g load were made for ferrite phase and were converted into tensile strength. Also, a series of plain carbon steel with carbon ranging from 0.06% to 0.8% were supercritically annealed then water quenched to obtain fully martensitic steels. These steels were subsequently tensile tested to simulate the tensile strength of martensite in the dual phase steels.

3. Experimental results

The intercritically heat-treated steels contained ferrite plus martensite. Fig. 1 shows the optical micrograph of 0.19% steel annealed at 800° C for 10 min followed by water quenching. The martensite regions were interconnected along the prior austenite grain boundaries. The lath size or plate size of martensite in dual phase steels as well as in the fully martensitic steels was about 0.2 to 0.4 μm. Grain size of ferrite in dual phase steels was about 6 to 10 μm. X-ray diffraction revealed that there was no retained austenite in the dual phase steels. Fig. 2 shows the tensile strength of dual phase

TABLE I Chemical compositions of the steels (wt %) and calculated AC1 and AC3 temperatures (° C)

Steels	C	Si	Mn	P	S	AC1	AC3
0.10% C	0.10	1.93	1.45	0.006	0.003	764	884
0.14% C	0.14	2.07	1.54	0.008	0.003	767	876
0.19% C	0.19	2.09	1.43	0.008	0.004	769	866

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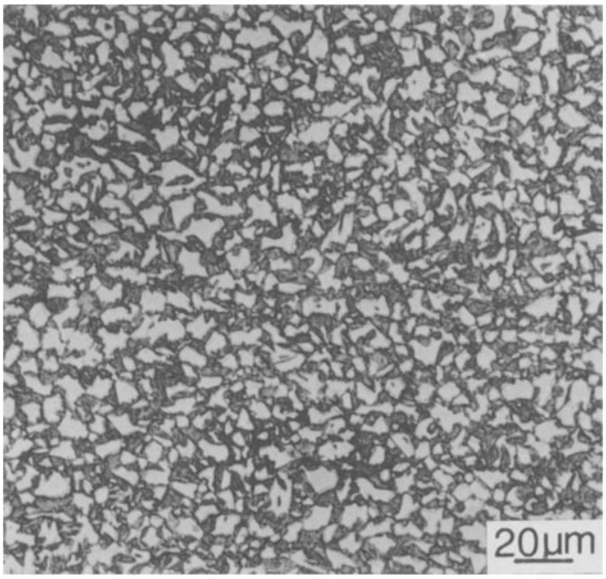

Figure 1 Optical micrograph of 0.19% C steel annealed at 800°C for 10 min followed by water quenching. V_m is about 0.52.

steel as a function of martensite volume fraction. It can be noted that the tensile strength of the dual phase steels increase more rapidly with increasing V_m up to about 0.4 than for greater V_m. That is, the tensile strength of dual phase steels deviates from the linear correlation to the volume fraction of martensite. Furthermore, the tensile strength also increases with increasing carbon content at constant volume fraction of martensite. Fig. 3 shows the tensile strength, converted from Vickers microhardness, of ferrite as a function of martensite volume fraction. It is obvious that the tensile strength increases with martensite volume fraction regardless of the different carbon content of the dual phase steels. This might be due to higher dislocation density in ferrite when the volume fraction of martensite increases [11]. The variation of tensile strength of ferrite with volume fraction of martensite can be obtained using a least squares fit,

$$S_f(\text{MPa}) = 497 + 67V_m \qquad (2)$$

The ultimate tensile strength of fully martensitic steels plotted against carbon content is shown in Fig. 4. Other results [5] which were converted from martensite hardness to tensile strength, are also presented. Pickering [12] has suggested that the solute

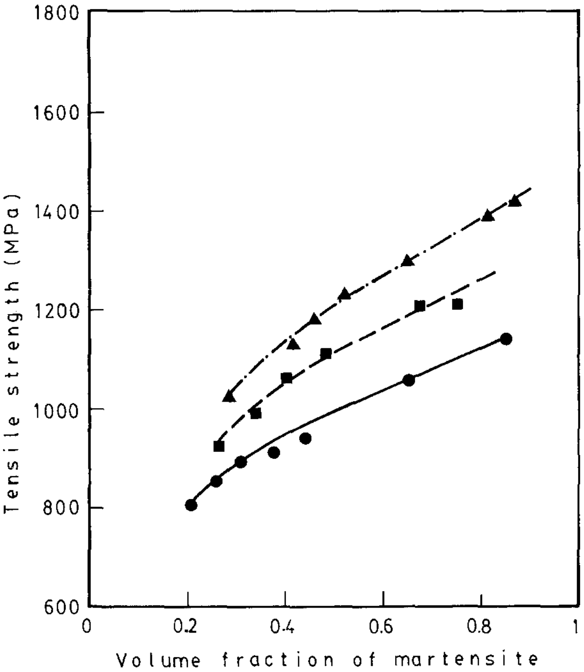

Figure 2 Tensile strength of dual phase steels as a function of martensite volume fraction. Steels were intercritically annealed followed by water quenching. (—·—▲—·— 0.19% C steel, ---■--- 0.14% C steel, -●- 0.10% C steel).

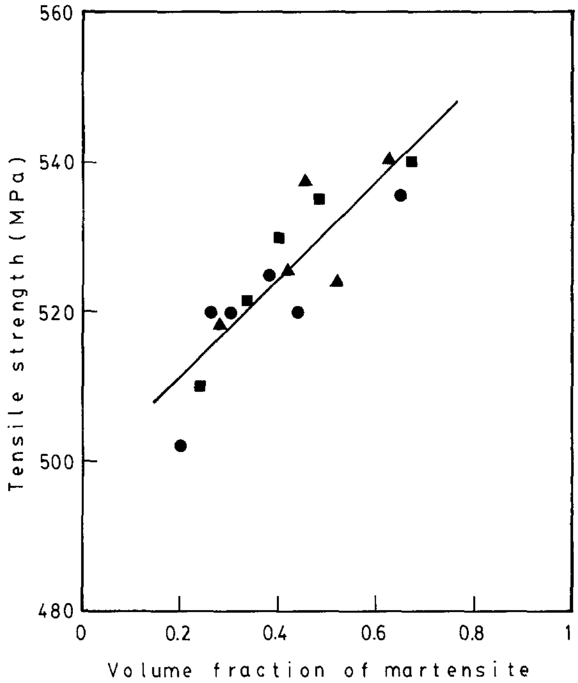

Figure 3 Tensile strength converted from Vickers microhardness of ferrite phase in the dual phase steels as a function of martensite volume fraction. Steels were intercritically annealed followed by water quenching. (▲ 0.19% C steel, ■ 0.14% C steel, ● 0.10% C steel).

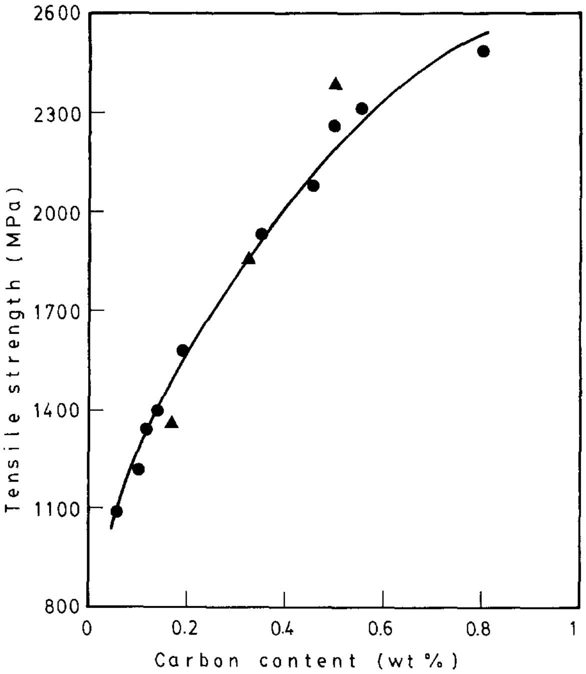

Figure 4 Effect of carbon content on the tensile strength of martensite. Steels were supercritically annealed followed by water quenching. (● present work, ▲ [5]).

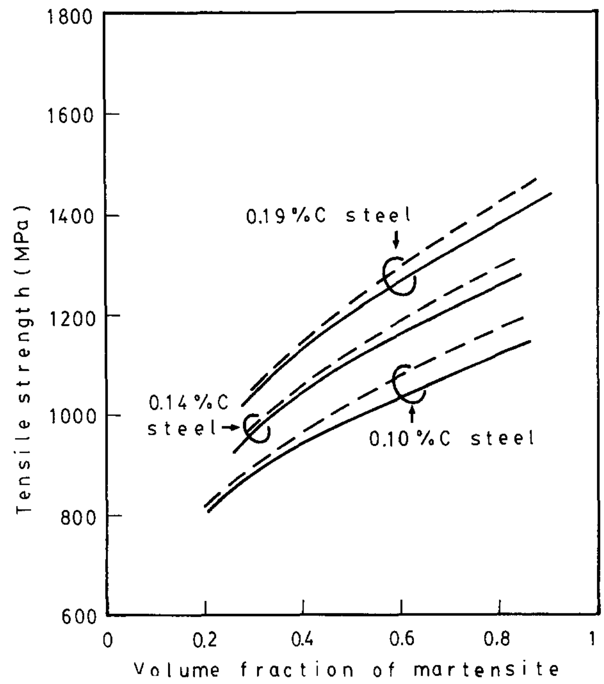

Figure 5 Comparison of predicted (- - -) and experimental (——) tensile strength with volume fraction of martensite.

strength is proportional to the square-root of the solute concentration. Therefore, the tensile strength of martensite as a function of carbon content can be obtained using a least squares fit

$$S_m(\text{MPa}) = 541 + 2289(C_m)^{1/2} \qquad (3)$$

where C_m is the carbon content (in wt %) of martensite.

4. Discussion

Since the density of the ferrite is similar to that of martensite (the ratio is about 1 : 1.025 [13]), the total carbon content of dual phase steels can be expressed as follows

$$C_d = C_m V_m + C_f(1 - V_m) \qquad (4)$$

where C_d is the total carbon content (in wt %) of dual phase steels and C_f is the carbon content of ferrite phase. Therefore, the carbon content of martensite in dual phase steel can be estimated by the following equation

$$C_m = (C_d - C_f)/V_m + C_f \qquad (5)$$

In general, C_f is less than 0.02%, from Equation 5, it is apparent that carbon content in martensite is proportional to the total carbon content in the dual phase steels for fixed V_m. Fig. 2 shows that the tensile strength increases with increasing carbon content of dual phase steels. This indicates that the carbon content in martensite has an effect on the tensile strength of dual phase steel. This result is different from that of Davies [6].

Transmission electron microscope observation showed that the lath or plate size of martensite in fully martensitic steels is similar to that in dual phase steels. Therefore, it is reasonable to assume that Equation 2 can be used to represent the tensile strength of martensite in dual phase steels. Substituting Equations 2, 3 and 5 into Equation 1, we obtain

$$S_d(\text{MPa}) = 497 + 2289 \cdot V_m[(C_d - C_f)/V_m + C_f]^{1/2} + 111V_m - 67V_m^2 \qquad (6)$$

Equation 6 shows that the strength of dual phase steels would not linearly dependent on the martensite volume fraction. Also, for fixed martensite volume fraction, the strength of dual phase steels would increase with increasing its total carbon content, in accordance with the experimental results. The calculated (taking C_f to be 0.02%) together with the experimental results are plotted in Fig. 5 (the data points have been left out for the sake of clarity). Fig. 5 shows good agreement between the calculated and measured values of tensile strength as a function of volume fraction of martensite although the former is slightly higher than the latter, especially at high V_m.

Equation 6 is based on the assumption that at the necking point of dual phase steel, both ferrite and martensite reach their ultimate tensile strength. This assumption is reasonable for ferrite according to the observation of Szewczyk *et al.* [14]. Therefore, the fact that the predicted tensile strength is seen to be slightly higher than the experimental one suggests that martensite never reaches its ultimate tensile strength even when the necking of dual phase steels occurs. This is similar to other investigators' results [5, 9, 14, 15].

5. Conclusions

The Fe–2% Si–1.5% Mn–C water quenched dual phase steels were investigated. It is confirmed that the tensile strength of dual phase steels depends on the tensile strength as well as the volume fraction of the martensite phase. Also, it is suggested that martensite may not deform up to its ultimate tensile strength when the bulk necking of the dual phase steels occurs.

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