INFLUENCE OF MARTENSITE CONTENT ON TENSILE PROPERTIES OF DUAL-PHASE STEEL

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الملخص

تم تحضير سلسلة من العينات من الصلب ذى الطورين تحتوى على المارتنسيت المتناثر بنسب حجمية تتراوح ما بين 22 إلي 47% عن طريق التبريد الفجائي من نطاق درجات حرارة إستقرار الفريت والأوستنيت لصلب يحتوى على 0.11% كربون و 0.12% سيلكون و1.2% منجنيز.

لوحظ أن المقياس المتوسط لطول قاطع حبيبات طور الفريت يتزايد في حين أن متوسط طول قاطع حبيبات المارتنسيت يتناقص كلما زادت النسبة الحجمية لطور المارتنسيت في بنية الصلب.درست مخططات الإجهاد و الإنفعال أثناء التشكيل اللدن باختبار الشد عند معدل إنفعال ثابت مقداره $8x10^{-4}$ لكل ثانية عند درجة حرارة الغرفة. لوحظ أن المقاومة القصوى للشد وإجهاد الخضوع يتزايدان مع زيادة النسبة الحجمية لطور المارتنسيت. كما وجد أن سلوك الاصلاد الانفعالي بناء على تحليل جيول كروسارد (Jaoul-Crussard) لجميع العينات ذات النسب الحجمية المختلفة من طور المارتنسيت قد حدث على مرحلتين بآليتى تشكيل مختلفتين.

ABSTRACT

A series of samples of a dual-phase steel containing finely dispersed martensite with different volume fractions (V_m), varying from 22 to 47%, were produced by intercritical annealing of 0.11C-0.12Si-1.2Mn steel.

The mean intercept length for ferrite increases, whereas the mean intercept length for martensite decreases, with increasing volume fraction of martensite. The deformation characteristics of the samples have been obtained at a constant strain rate $8x10^{-4}$ s^{-1} at room temperature. Both the yield and tensile strengths were observed to increase with the volume fraction of the martensite**.** Jaoul-Crussard analysis of the work-hardening behavior of the samples showed two distinct stages of plastic deformation.

KEYWORDS: Heat treatment; Ferrite; Martensite; Dual phase microstructure; Mechanical properties; Tensile fracture

INTRODUCTION

Dual Phase (DP) steels are one of the family members of high strength low alloy (HSLA) steels with a very good combination of strength and ductility [1-5]. DP steels also have the advantage of reduced cost, superior formability, and excellent surface finish over other HSLA steels.

The conventional heat treatment of dual-phase steel consists of annealing within the inter-critical temperature, ($\alpha+\gamma$) phase field, followed by quenching. This heat treatment converts the austenite to martensite; the microstructure of DP steel thus consists of hard martensite dispersed in soft, ductile ferrite matrix, accounting for 50 to 90% of volume. The martensite imparts high strength and the ferrite matrix good elongation resulting in a desirable combination of strength and ductility [6]. In addition to martensite the steels also contain some amount of retained austenite [7]. Much against expectations, the amount of retained austenite has been shown to be quite significant; about 10 % [8-9].

A high work-hardening rate along with excellent elongation give DP steels much higher ultimate tensile strength than that of conventional steels of similar yield strength. The dual phase steels exhibit lower YS/UTS ratio compared to their single phase analogs [10]. The properties of these constituents of the DP steels depend on the composition of the austenite at the intercritical annealing temperature and upon the cooling rate.

Previous investigations have revealed that DP steels possess a number of unique properties making them attractive for applications in automotive industry. The specific properties of these steels allow reducing weight of automobile components, e.g. car body panels, wheel discs, rims and bumpers [11-12]. Dual phase steels have also potential for wear resistant applications like pipelines for transporting mineral slurries [13]. Dual phase steels have a better deformability than other HSLA steels with similar strength [14,15].

Mechanical properties of dual phase steels are affected by several factors, among which the volume fraction and morphology of martensite [16,17] and the ferrite grain size [18,19]. Combined effects of these factors, however, have not been yet fully quantified. Such quantification is the subject of this study, which investigates the effect of the martensite volume fraction on the geometrical characteristics of the grains of the constituent phases as well as on the strength, ductility and work hardening characteristics of the DP steel.

EXPERIMENTAL TECHNIQUE

Sample preparation and heat treatment

The present investigation has been conducted on a series of samples of carbon-manganese steel subjected to heat treatment at varying inter-critical annealing temperatures to obtain two phase structure with different volume fractions of martensite. The chemical composition of the material used in this study is shown in Table (1). The material was supplied in the form of hot rolled 24 mm round bar. The samples for tensile testing were cut from the as-received hot rolled rods. The dimensions of the test pieces were produced according to ASTM E8 specifications [20], as shown in Figure (1).

Table 1: Chemical composition of the investigated steel (wt. %)

C	Mn	Si	P	S	Cr	Ni	Mo	Cu	Fe
0.11	1.2	0.12	0.04	0.02	0.06	0.08	0.01	0.12	balance

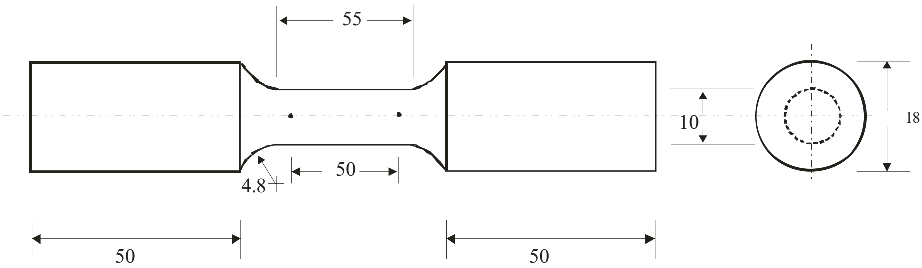

Figure 1: Dimensions of the tensile test specimens (in mm)

The Ac_1 and Ac_3 temperatures, which define the ferrite + austenite region, were calculated for the investigated steel by Andrews empirical equations and found to be 720 and 840^{o}C, respectively. Tensile specimens were subjected to intermediate quench (IQ), consisting of a double operation. The specimens were first soaked at 900^{o}C for 30 minutes and quenched in a mixture of ice and brine (10% table salt solution in water), in order to obtain martensitic structure. The specimens were subsequently held at intercritical temperatures of 730, 750, 775, and 800^{o}C for 20 minutes, to be finally quenched in the same cooling medium as schematically shown in Figure (2). The temperature during annealing was maintained within ± 2^{o}C.

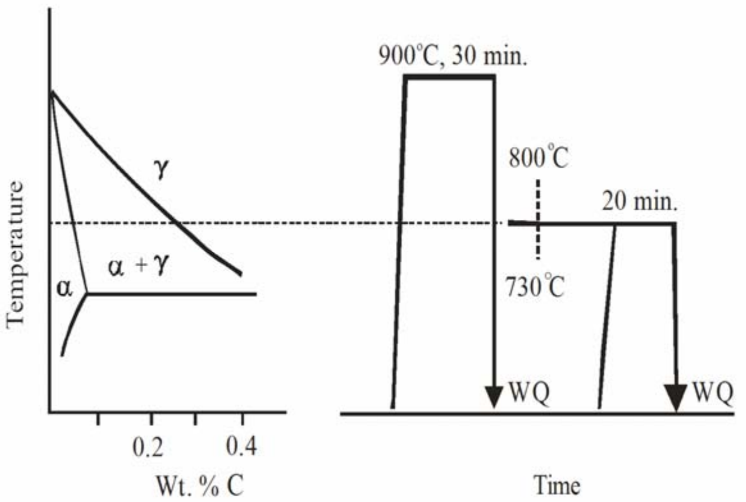

Figure 2: Schematic representation of heat treatment schedules IQ treatment

Mechanical properties

Mechanical properties were evaluated by conducting tensile tests of specimens, heat treated at various inter-critical temperatures. The tensile specimens were deformed at room temperature with the strain rate $(d\varepsilon/dt) = 8.3*10^{-4}s^{-1}$ using a tensile tester (810 Material Test System, 100 kN load capacity). An extensometer of 50mm gauge length was used for strain measurements. At least three specimens were subjected to tensile testing for each heat treatment condition. Engineering stress-strain curves were obtained from the tensile tests. Tensile fracture surfaces were cleaned and investigated under a scanning electron microscope (Model: S-2600N Hitachi).

Microstructure Examination

The microstructures of the specimens were investigated via light microscopy of transverse and parallel sections cut from the grips of the tensile specimens. The metallographic samples were prepared using standard techniques. In order to reveal the microstructure the samples were etched in a 2% nital solution. From each section, up to 5 fields of observations have been randomly selected and recorded for image analysis.

Measurements of volume fraction were carried out using an image analyzer with dedicated software [21]. The volume fraction of ferrite (V_f) as well as the mean intercept length for ferrite and martensite grains (λ_f and λ_m respectively) have been estimated from stereological measurements, executed using the image analyzer. Geometrical parameters of the individual grain sections which have been used in this study are listed in Table (2).

Table 2: Geometrical parameters used to characterize the grain geometry

Parameter (dimension)	Interpretaion
V_v	volume fraction of the dispersed phase
λ_f	the mean intercept for ferrite
λ_m	the mean intercept for martensite

RESULTS AND DISCUSSION

Microstructural Investigation

The employed heat treatment operation resulted in two phase structures in all samples. These structures consist of a soft ferrite matrix, a dispersed hard martensite and a small volume fraction of retained austenite islands. The volume fraction of martensite varied from 20-45%.

In order to characterize the microstructures in the investigated samples subjected to intercritical treatment conducted at various temperatures, light micrographs have been taken from the as-treated specimens. Figure (3) illustrates these structures, which reveal phase transformations induced by the intercritical annealing.

The mean intercept length for ferrite and martensite in the specimens subjected to annealing at different IQ temperatures are shown in Figure 4 as a function of martensite volume fraction. It is seen that, λ_f increases, whereas λ_m decreases, with increasing volume fraction of martensite. It can be noted from the plot in Figure (4) that:

a) The intercept length for ferrite grains linearly correlates with the volume fraction of martensite.
b) The intercept length of martensite exhibits a negative trend with increasing V_m.

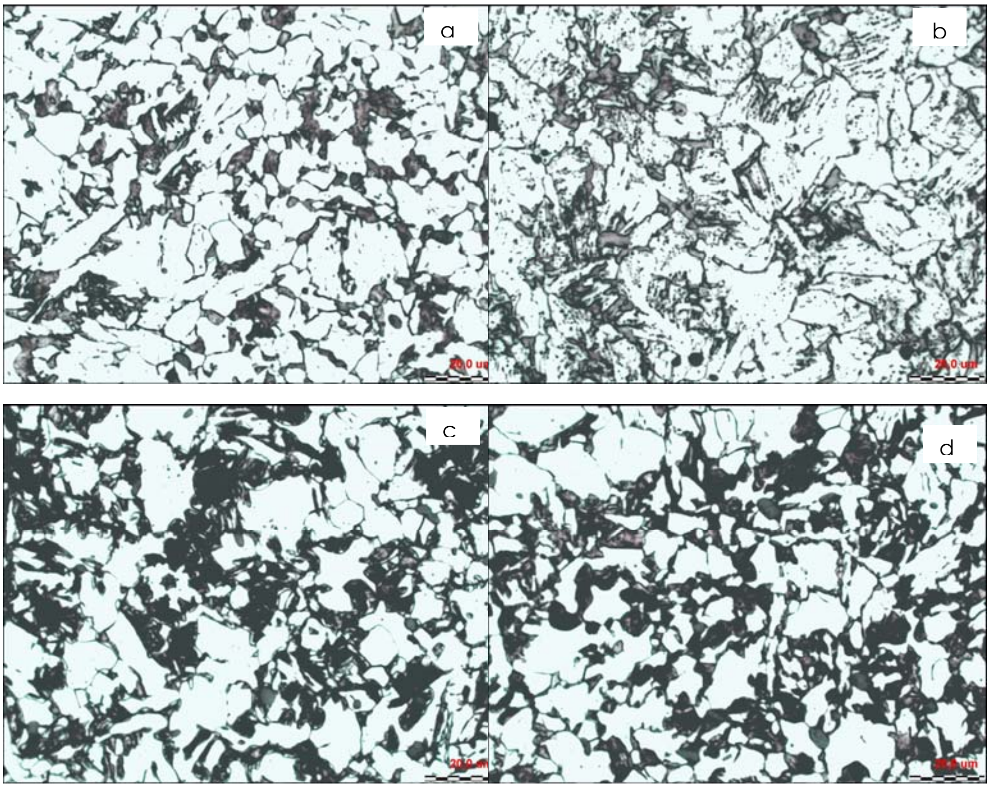

Figure 3: Typical light microscopy images of dual-phase steels showing dispersion of martensite (black block), and ferrite (white). Micrographs (a), (b), (c) and (d) correspond to the microstructures obtained with IQ at 730, 750, 775 and 800°C, respectively.

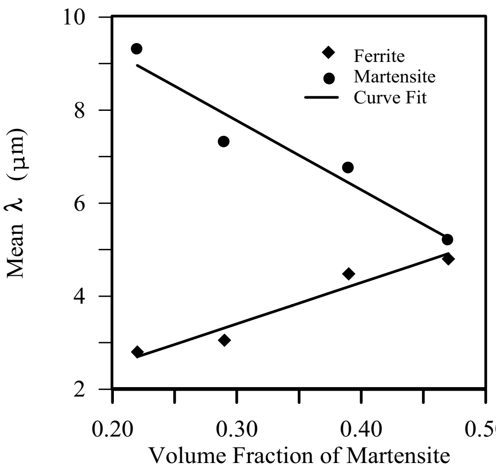

Figure 4: Mean intercept of ferrite and martensite grains plotted against the volume fraction of martensite

Table 3: Microstractural parameters and 0.2% proof stress to ultimate tensile strength ratio obtained from specimens inter-critically treated at various temperatures

Intercritical Temperature (°C)	Volume percent of ferrite $(\%V_f)$	Volume percent of martensite * $(\%V_m)$	$\frac{\sigma_{0.2\%}}{\sigma_{UTS}}$
730	78	22	0.48
750	71	29	0.51
775	61	39	0.49
800	53	47	0.49

* plus retained austenite

Stress-strain data

Figure (5) shows true strain-stress curves for specimens with various martensite volume fractions. All curves exhibited continuous yielding and rapid initial strain hardening rate, characteristic for dual phase steels. These characteristics had been attributed to the high mobile dislocation density in the ferrite in the vicinity of the martensite particles, generated by the residual stresses resulting from the martensitic type of phase transformation, taking place during quenching. The rapid work hardening at low strains is due to the continuous plastic deformation mechanism involving transformation induced stresses and mobile dislocations [22]. The characteristic low values of the $\sigma_{0.2\%}/\sigma_{UTS}$ ratio, ranging between 0.47 and 0.51, are also shown in Table (3).

The values of proof stress ($\sigma_{0.2\%}$) and ultimate tensile strength (UTS) are plotted in Figure (6) versus martensite volume fraction (V_m). It is evident that these parameters are primarily controlled by the amount of the second phase. Linear regression of the data resulted in relations of the following approximate forms:

$\sigma_{0.2\%}(\text{MPa}) = 305 + 298\ V_m$ and $\sigma_{UTS}\ (\text{MPa}) = 630 + 576\ V_m$

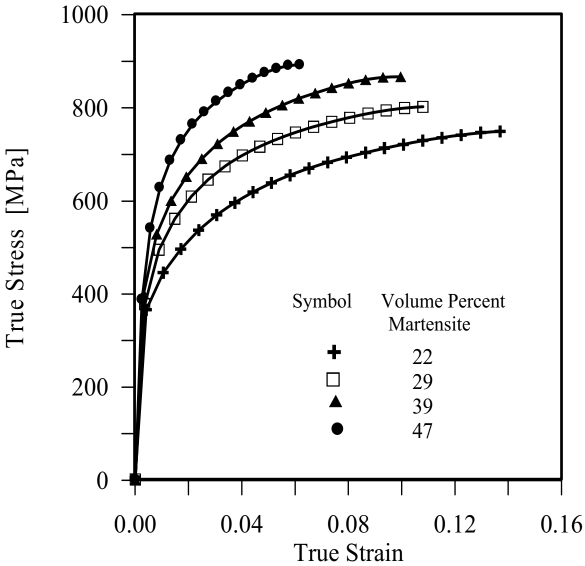

Figure 5: True stresses True Strain for various volume fraction of martensite

The linear increase in the yield strength versus volume fraction of martensite for dual-phase structures with ferrite matrix was previously noted by Davies [23].

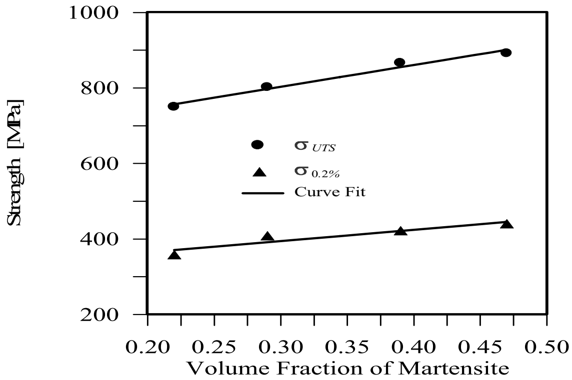

Figure 6: Variation of strength parameters with the relative amount of martensite

The effect of martensite volume fraction on the uniform strain range also indicates a linear dependence as shown in Figure (7). Linear regression of the data resulted in a relation of the following approximate form:

$$\delta = 0.205 - 0.3\ (V_m)$$

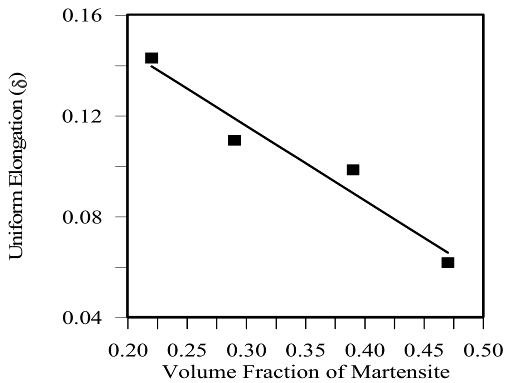

Figure 7: Effect of the martensite volume fraction on the uniform deformation extent

Work-hardening characteristics (Modified Crussard-Jaual analysis)

The work hardening behavior of dual phase steel was analyzed using the modified Crussard-Jaual (C-J) method [24] which is based on the modified Swift relation [25]:

$$\varepsilon = \varepsilon_o + K\sigma^m$$

where ε and σ are the true plastic strain and true stress respectively, ε_o and K are constants, and m is the strain hardening exponent. The logarithmic from of the modified Swift relation, differentiated with respect to σ is:

$$\ell n(d\sigma / d\varepsilon) = (1 - m)\ell n(\sigma) - \ell n(Km)$$

The parameters K and m are usually determined form a plot of $\ell n(d\sigma/d\varepsilon)$ versus $\ell n(\sigma)$. The analysis according to the modified Swift equation was employed in this study. As shown in Figure (8), the corresponding plot of the present data does not obey the simple linear relationship. It is seen that the dual phase steel deforms in two distinct stages. This two stage strain hardening behavior of dual phase steel has been reported earlier [26-27].

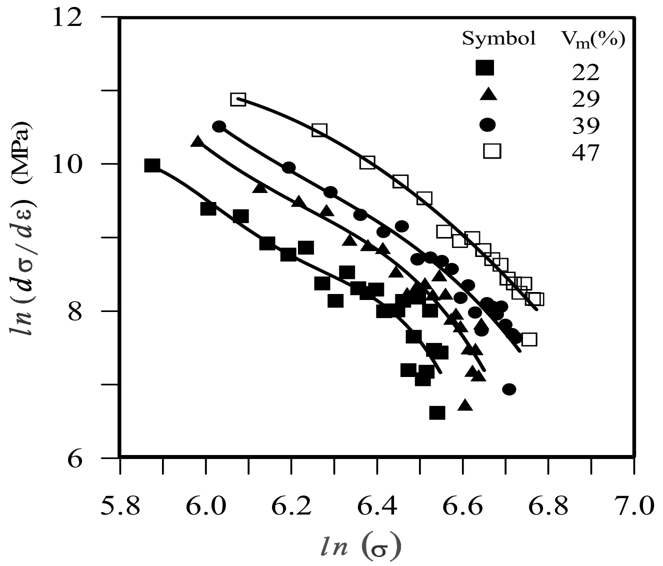

Figure 8: Representative experimental $\ln(d\sigma/d\varepsilon)$ **versus** $\ln(\sigma)$ **curves for different volume fractions of martensite**

However, to a first approximation, all curves yield close values of **m** slightly increasing with the volume fraction of martensite as shown in Table (4). The constant **K**, on the other hand, strongly depends on V_m as shown in Figure (9).

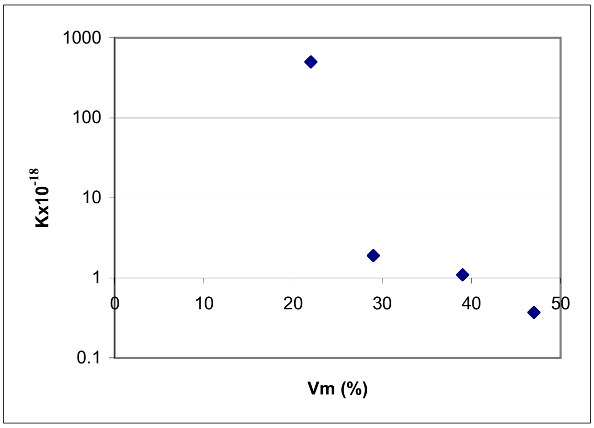

Figure 9: K values for different volume fractions of martensite, V_m

The results, obtained in this work indicate a strong influence of V_m on the flow stress of DP steels. However, the effect of the martensite volume fraction is "mitigated", probably by the accompanying change in the grain geometry of the structural constituents.

Table 4: Estimations of m and K values vs. volume fraction of martensite, V_m

$(\%V_m)$ Volume percent of martensite	approximate form	m	K
22	$\ell n(d\sigma/d\varepsilon) = -4.01\ \ell n(\sigma) + 33.62$	5.01	$5x10^{-16}$
29	$\ell n(d\sigma/d\varepsilon) = -4.08\ \ell n(\sigma) + 39.20$	5.08	$1.9x10^{-18}$
39	$\ell n(d\sigma/d\varepsilon) = -4.76\ \ell n(\sigma) + 39.61$	5.76	$1.1x10^{-18}$
47	$\ell n(d\sigma/d\varepsilon) = -4.80\ \ell n(\sigma) + 40.67$	5.8	$3.7x10^{-19}$

Conclusions

On the basis of the experimental work that has been carried out and presented in this article, the following conclusions can be drawn.

- The intercept length for ferrite grains linearly correlates with the volume fraction of martensite while the intercept length of martensite exhibits a negative trend with increasing V_m.
- The yield as well as the ultimate tensile stresses of dual-phase steel linearly increases with the martensite volume fraction.
- The total uniform deformation decreases linearly with the volume fraction of the martensite phase.
- Dual-phase steels are characterized by an exceptionally high initial work-hardening rate, which rapidly decreases with increasing the amount of strain. The decrement is larger the higher is the volume fraction of martensite.
- The work hardening rate versus stress plot was generally found to be nonlinear. The modified CJ analysis showed that the present dual phase steels deform in two stages over a uniform stain range

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