

STUDY ON WORK HARDENING BEHAVIOR OF FERRITIC-BAINITIC DUAL PHASE STEELS

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ABSTRACT

In this work, the stress-strain curve of two types of dual phase steels namely ferritic-bainitic and ferritic-martensitic with 0.16% C and 1.2% Mn have been obtained using tensile tests. Ferritic-Bainitic dual phase steels were intercritically annealed under different conditions and subsequently quenched in a salt bath, while Ferritic-Martensitic dual phase steels were water quenched. The stress-strain data were checked using Hollomon's equation. The results showed that both types of dual phase steels had two stages of work hardening and each stage had a different work hardening exponent. The effect of volume fraction of hard phases (bainite and martensite) on ultimate tensile strength, total elongation and work hardening exponent were also investigated. The results indicated that increasing the volume fraction of hard phase increases the UTS while decreases the work hardening exponent and total elongation.

Keyword: dual phase steels, Work hardening, Ferrite, Bainite, Martensite, Mechanical properties.

1. INTRODUCTION

Dual-phase (DP) steels developed over the past few decades offer impressive mechanical properties, such as continuous yielding behavior and superior strength–ductility combination, in addition to the advantage of reduced cost, better formability, and excellent surface finish over other high-strength low-alloy (HSLA) steels [1]. The development of DP steels has become interest in the automobile and truck industries, because of the potential of weight reduction by using inexpensive alloying without sacrificing mechanical properties [2, 3].

DP steels usually consist of some specific volume fraction of high-strength phase, such as martensite or bainite, contained within a softer matrix, ferrite [4]. These steels are produced by either intercritical annealing or controlled rolling [1]. However, investigations on ferrite–martensite dual phase (FMDP) steels are extensive compared with that ferrite bainite dual phase (FBDP) steels. In addition,

reports related to the structure–property relations of ferrite–bainite dual-phase steels of low carbon grades are limited [1]. The present report is aimed to understand the work-hardening behavior of FBDP steels vis-à-vis FMDP steels of low carbon variety containing higher volume fractions of the harder phase.

Noticeable attempt has been directed toward developing semi-empirical relations that describe the flow behavior of polycrystalline materials. Relationships proposed by Hollomon, Ludwik and Swift are the constitutive equations most commonly used to describe the true stress-strain behavior of these materials. The parameters involved in these constitutive equations have been used to investigate the underlying mechanisms and changes in microstructures that occur during deformation [5].

The plastic flow behavior of many metals and alloys can be described by the Hollomon relation [5] as follows:

$$\sigma = k\varepsilon^n \text{ (A)}$$

That k and n are fitting constants usually termed as work-hardening coefficient and work-hardening exponent, respectively. By plotting the stress–strain data on a double logarithmic plot and fitting to a straight line at higher strain levels, these parameters can be evaluated. The slope of the line gives the n value and the intercept at $\varepsilon = 1$ gives the k value. In an ideal case these two flow parameters should describe completely the shape of the true stress–strain curves. The value of k provides some indication of the level of the strength of the material and of the magnitude of forces required in forming, whilst the value of n correlates the slope of the true stress–true strain curve, which provides a measure of the ability of the material to retard localization of deformation. It should be noted that the work-hardening parameters k and n are of considerable technological importance [6]. The n value is less than unity, but for metals it usually varies between 0.1 and 0.6 and increases with decreasing strength [7]. The exponent n is an important parameter for two reasons. It signifies the work-hardening characteristic of a material, that is, the higher the value of n , the higher is the rate at which the materials work hardens. A material with a high value of n is preferred for processes which involve plastic deformation. The second reason for its significance is that it is an indicator of the stretch formability of a material. The larger the n value, the more the material can deform before instability, and the material can be stretched further before necking

starts. This is so because n equals the true strain at the ultimate tensile strength, which is the limiting value of strain for uniform deformation [6-8].

However, several previous investigators indicated that a large number of materials such as dual phase steels do not obey this relation strictly. For these materials the variation of $\ln \sigma$ with $\ln \epsilon$ is nonlinear. This means that only one n or K cannot describe the flow and work hardening behavior of these materials. They showed that dual phase steels show two stage hardening followed by two work hardening indices [1, 6, 9-13].

In this study, the experimental data for flow behavior of DP steels were fitted to Hollomon equation and work-hardening exponent (n) of FBDP steels and FMDP steels were compared.

2. EXPERIMENTAL PROCEDURE

Commercial low carbon steel has been used in this investigation. The steel was available in the form of 2 mm thick sheet. The chemical composition of the steel is shown in Table 1. A_{c1} and A_{c3} transformation temperatures of this steel were calculated from the empirical formula [14], which are 715 and 840 °C respectively.

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

C	Mn	Si	S	P	Al	Cr	Fe
0.16	1.2	0.1	0.015	0.005	0.089	0.155	base

Specimens of 30 mm width and 250 mm length were cut from the steel sheet and were first subjected to heat treatment for achieving ferrite–bainite structures. This heat treatment consisted of the following sequential steps: (a) normalizing the steel at 920 °C for 30 min and air cooling, (b) intercritically annealed at 760, 785 and 810 °C for 15 min (c) isothermally held at 370 °C for 30 min in salt bath (d) air cooling to room temperature. The heat treatment schedules to produce dual-phase ferrite–bainite steel is schematically shown in Fig. 1.

Samples for microstructure studies were prepared and etched with 2% nital solution. The volume fractions of the different phases in the dual-phase microstructures were measured by point-counting technique according to ASTM E

562-83. Tensile specimens were prepared with a gauge length of 50 mm. Tensile tests were carried out at room temperature using a tensile machine with strain rate of $1.3 \times 10^{-3} \text{ s}^{-1}$.

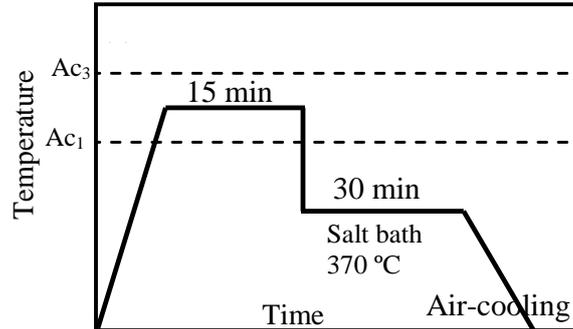


Fig. 1. Schematic representation of the heat treatment schedules for obtaining ferrite–bainite microstructures.

3. RESULTS AND DISCUSSION

3.1. Microstructure

Microstructure observation showed that intercritical annealing and quenching in salt bath create ferrite-bainite structure. Light micrographs of steels with different V_b (volume fraction of bainite) are shown in Figs. 2. The employed heat treatment at 760, 785 and 810 °C led to different combination of ferrite–bainite microstructure having bainite volume fraction (V_b) of 21.7, 30.2 and 52% respectively.

During intercritical annealing, austenite forms in two steps. The first step is transformation of pearlite to austenite and then the second step is dissolution of ferrite in the newly formed austenite [15]. Because of rapid transformation of pearlite to austenite [15], in investigated structure no pearlite appears. It means that the first step of austenite formation (transformation of pearlite to austenite) complete after 15 min at all temperatures.

In FBDP steels after annealing at 760 °C, amount of bainite was 21.7% which is the result of pearlite transformation and some dissolution of ferrite in austenite. An increasing of 25 °C in temperature for the same annealing time (15 min) causes 8.5% increase in bainite content. It means increasing temperature causes more dissolution of ferrite in austenite (step two).

The rate of austenite formation in second step depends highly on temperature and increases with increasing temperature [16]. Thus increasing temperature from 785 °C to 810 °C in FBDP steels, causes 19.8% increase in bainite content which is higher than the 8.5% increase due to temperature rise from 760 °C to 785 °C. By increasing dissolution of ferrite in the austenite, carbon content of austenite decreases which can affect bainite hardness [17].

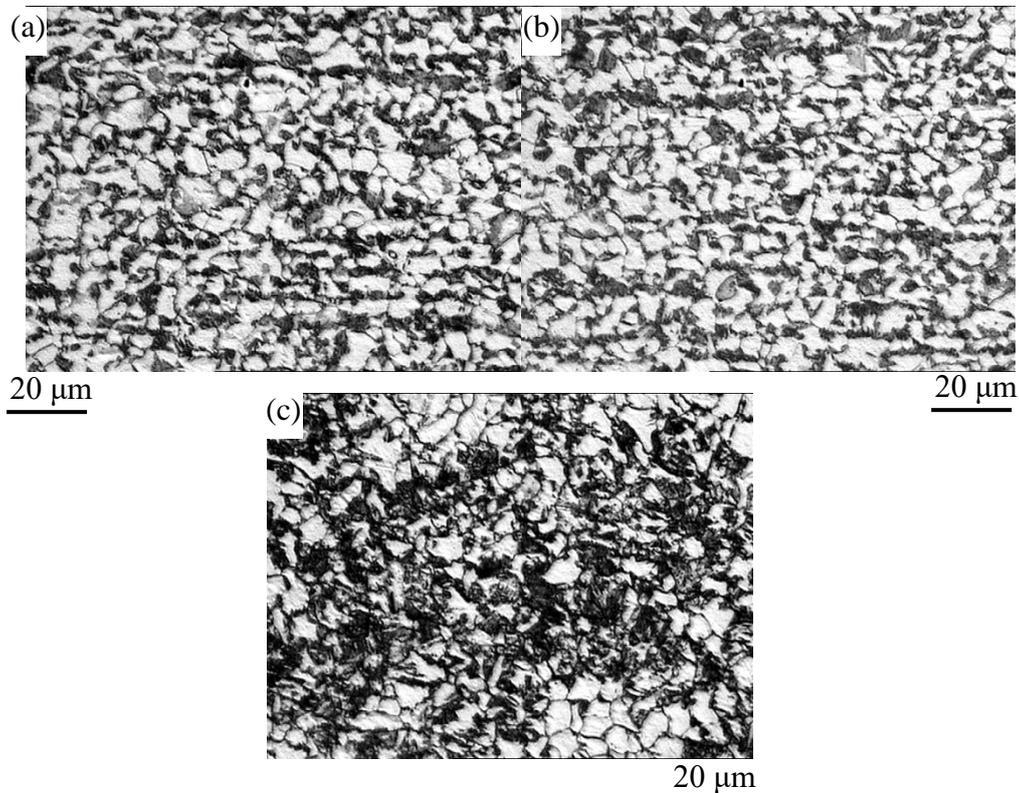


Fig. 2. Microstructures of studied steel containing: (a) 21.7%, (b) 30.2% and (c) 52% of bainite Vol. %. The white constituent is ferrite whereas the black constituent is bainite.

3.2. Ultimate tensile strength and total elongation

Variation of ultimate tensile strength (σ_{uts}) of these steels with volume fractions of hard phases (V_{HP}), bainite, are shown in Fig. 3. The total elongation changes with V_{HP} are also plotted in Fig. 4. As can be seen in Figs. 3 and 4, ultimate tensile strength increases linearly with increasing V_{HP} , while total elongation decreases.

According to low of mixture the strength of DP steels is related to volume fraction and strength of hard phase and increases with increase of volume fraction and strength of hard phase. Thus FBDP generally has lower strength in compare of FM DP steels because of lower strength of bainite compared to martensite at the same carbon content [18].

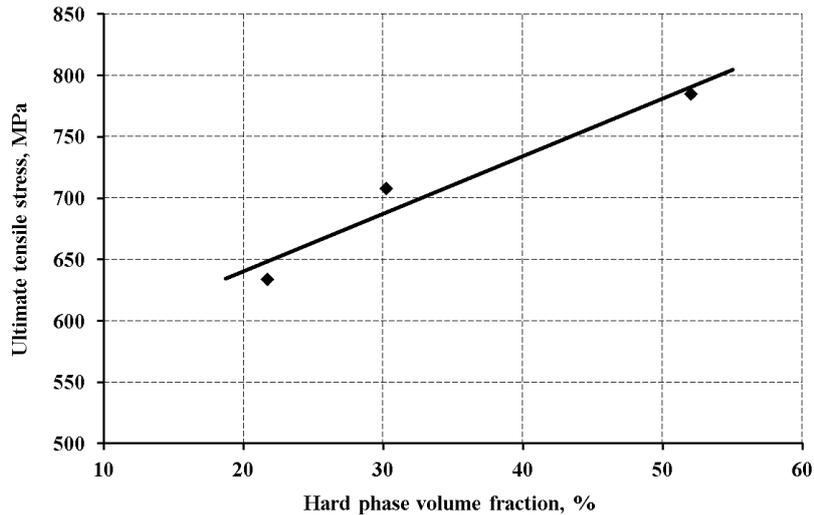


Fig. 3. UTS as a function of hard phase volume fraction in FBDP steels.

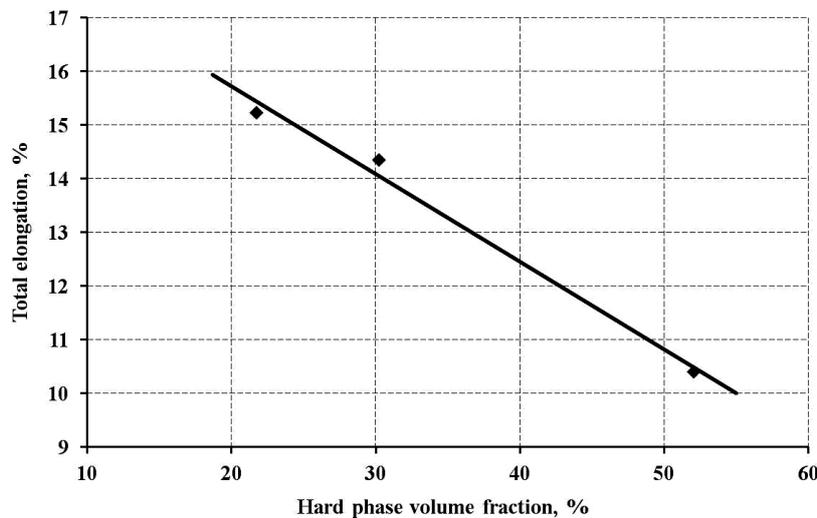


Fig. 4. Total elongation as a function of hard phase volume fraction in FBDP steels.

3.3. Work hardening

Fig. 5 shows typical $\ln \sigma - \ln \epsilon$ plots of FBDP steels with different V_{HP} at room temperature. Nonlinear variations of $\ln \sigma$ with $\ln \epsilon$ indicate that the investigated FBDP steels, with different volume fraction of bainite and martensite, show the two stages of work hardening mechanisms. The first stage has a high strain hardening exponent, while the second stage has a low one. These results are in agreement with the previous works on work hardening behavior of dual phase steels [1, 6, 9-13]. According to these works the first stage associated with plastic deformation of ferrite matrix and the second stage associated with plastic deformation of both ferrite and martensite or bainite.

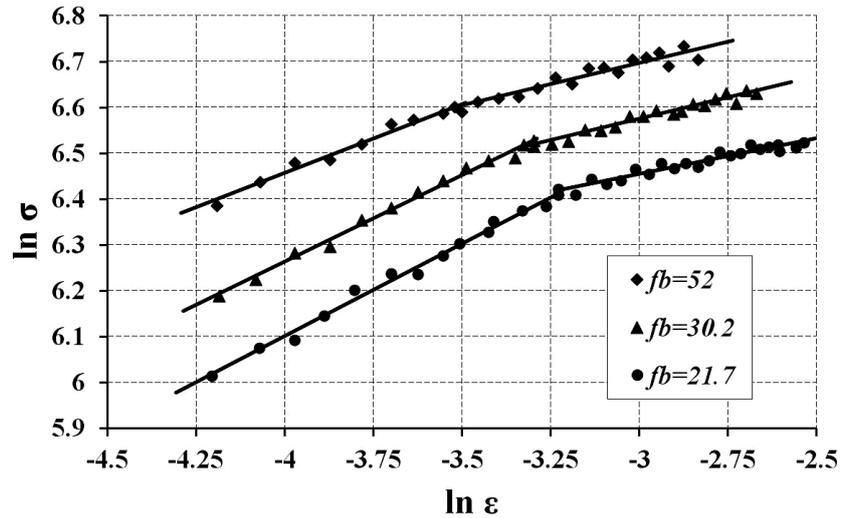


Fig. 5. Typical ln–ln plot of true stress vs. true strain for investigated FBBDP steel with different V_b .

Spiech and Miller [18] have proposed that increased dislocation density in ferrite region due to the generation of necessary dislocations, and relaxation of residual stresses due to small plastic strain affect strain hardening in DP steels. In fact transformation of retained austenite to martensite during heat treatment leads to increase in dislocation density in ferrite, which subsequently influences strain hardening. Investigations related to the deformation behavior of FBBDP steels, on the other hand, are limited in number. Kumar et al. [1] have suggested that strain partitioning between bainite and ferrite is less compared to that between martensite and ferrite.

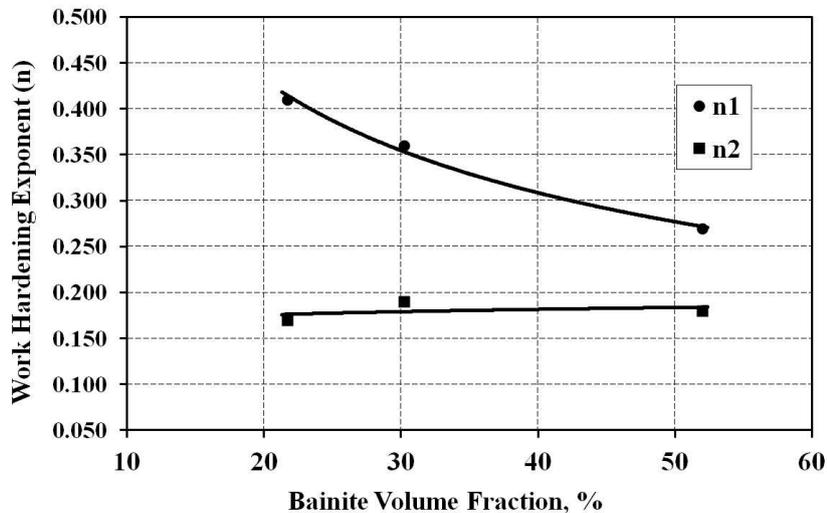


Fig. 6. Work hardening exponent as a function of V_b in FBBDP steels.

Residual stresses and dislocation density resulting from transformation is lower in the case of FBBDP steels compared to that in FMDP steels and these factors would

assist easy dislocation movement. Thus, the reason for higher n_1 value of FBDP steels compared to that of FMDP steels can be considered to originate from the low dislocation density in the FBDP steels. Low residual stresses and dislocation density in the case of FBDP steels compared to that in FMDP steels related to lower volume change in transformation of austenite to bainite compared to martensite [18].

It is already mentioned that the strain-hardening exponent of stage I of FBDP steels decreases with increasing volume fraction of martensite and bainite. Cribb and Rigsbee [19] have shown that n ranges from 0.25 to 0.14 with hard phase content of 15–50% in FMDP steel. The magnitude of stage I work hardening (n_1) for the selected steel is found to vary from 0.41 to 0.27 for bainite content between 21.7 and 52% for FBDP steels. Thus, the obtained nature of variation of n for the FBDP steels is in agreement with the example cited above.

The variation of n can analyzed using localized ferrite plastic strain (LFPS) that develops during austenite to martensite or bainite transformation in dual phase steels [1]. The LFPS is influenced by the extent of plastic zone in ferrite, the average dislocation density and the associated strain in ferrite. As the volume fraction of martensite or bainite increases in dual-phase steels, localized plastic strain increases. Thus, the decrease in n value for FMDP and FBDP steels with increasing volume fraction of martensite or bainite may be attributed to localized strain.

The variation of n with bainite content in low carbon steels with low content of bainite is not available in the existing literature. Thus the present results could not be compared with any earlier results. The localized plastic strain caused by generation of dislocations during bainitic transformation increases with increase in bainite content, but since bainite transformation takes place at 370 °C, the localized plastic strain is expected to be smaller compared with that in FMDP steels when steel quenches in water.

Work hardening exponent of stage II is lower than stage I which related to increase strength of the structures that deform in this stage (both ferrite and bainite). According to Figs. 6, there is little change in n_2 value with increasing V_b and n_2 slightly decreases with increasing V_b which can be related to the increase in strength by increasing V_b and V_m (Fig. 3).

4. CONCLUSION

The work hardening behavior of a series of ferritic–bainitic dual-phase steels

made from low carbon steel has been examined. The results of the investigation lead to the following conclusions:

1. FBDP steels showed two work hardening stages correspond with activated deformation mechanisms.

2. With increasing V_b , the work hardening exponent at stages I and II work hardening is decreased but the work hardening exponent at stage II was nearly independent of V_b .

3. FBDP steels have higher work hardening exponent at stages I and II compare to amount reported for FMDP steels.

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