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Effect of long duration intercritical heat treatment on the mechanical properties of AISI 4340 steel

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Ferrite-bainite dual phase (FBDP) steels are a class of steels characterized by a microstructure consisting of a soft ferrite matrix with hard bainite islands. The holding time in the dual phase ($\alpha + \gamma$) region is an important parameter in the intercritical annealing at constant temperature and influencing mechanical properties of this steel. Dual phases with various ferrite volume fractions (45–65 vol. %) were fabricated by changing the holding time. Samples of these steels with ferrite-bainite structure were tensile tested at room temperature. Results showed that as the ferrite volume fraction increased, the yield strength decreased but a different type of behaviour was observed for ultimate tensile strength (UTS) tests. UTS increased when the ferrite volume fraction (V_f) increased above ca. 55%. The tensile flow stress data for this steel, obtained from samples with various ferrite volume fractions, were analyzed in terms of the Hollomon equation. Two or three Hollomon equations can describe the flow behaviour adequately, and it was found that with increasing V_f the work hardening occurs in three stages, each equation belonging to one of these stages. Finally, variations of Hollomon equation parameters were used to explain the deformation mechanisms activated at various stages.

Keywords: *dual phase steels; ferrite; bainite; mechanical properties; work hardening*

1. Introduction

Dual phase steel is currently a material of commercial interest for certain automotive applications. The interest originates from the demand for lighter, more fuel efficient vehicles and the fact that the dual phase steels combine superior ductility, with good tensile strength, and in this regard their properties are very similar to plain carbon steels [1–3].

Dual phase steels usually contain some volume fractions of high-strength phase such as martensite or bainite, within a softer matrix, ferrite [4]. The ferrite matrix provides the ductility while the high strength particles provide strength. Besides these properties, other useful properties of these steels are low yield strength, continuous

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yielding behaviour, and highly uniform total elongation [5–8]. Mechanical properties of dual phase steels are affected by several factors, including; the volume fraction, the morphology of hard phase [9], and the ferrite grain size [4].

Investigations on ferrite-martensite steels are extensive compared with those on the structure–property correlations of ferrite-bainite dual phase (FBDP) steels. Only a few papers report on the salient aspects of the structure–property relations of ferrite -bainite (F-B) steels. Sudo et al. [10, 11] examined a few F-B steels, and reported that an increase in the bainite content generally increases their yield ratio (the ratio of yield strength to tensile strength), reduces the area and fatigue endurance limit.

The effect of the bainite content on ferrite-bainite-martensite steels has been examined by Sudo et al. [10, 11], Kim et al. [12] and Choi et al. [13]. Sudo and Iwai [10] indicated that a decrease in the bainite content in ferrite–bainite–martensite steels causes a lowering of the strength and yield ratio but leads to improved percentage elongation and strain hardening exponent. Kim et al. [12] suggested that small amounts of bainite in ferrite–martensite dual phase (FMDP) steels lead to an improvement in the yield strength and the ductility but to a deterioration in the tensile strength. These investigators have also reported the occurrence of discontinuous yielding behaviour in these multiphase steels.

Discontinuous yielding in three phase steels at slow strain rates has also been observed by Choi et al. [13]. In addition, attempts also were made to study the effect of bainite on TRIP aided dual phase steels [14, 15]. However, systematic studies on F-B dual phase steels with a wide range of bainite content are lacking.

In our previous investigations [16, 17] on ferrite-bainite DP steels with $V_f < 0.34$, it was concluded that with increasing ferrite volume fraction, the yield and ultimate tensile strength decrease, while elongation increases. Furthermore, for the considered range of V_f values, the existence of two distinct work hardening stages was ascertained for this particular steel under study. The ferrite and bainite strength is not unique value over any range of V_f but it may be functions of chemical composition, shape and continuity of phases, internal stresses due to phase transformation and plastic incompatibility etc. Some of these parameters such as phase chemical composition, shape and continuity of phases change with increasing V_f and other such as internal stresses due to phase transformation and plastic incompatibility change during deformation and affect the strength of DP steels.

The present research is aimed at understanding the structure–property (tensile) dependences of ferrite-bainite steels having ferrite volume fractions ranging from 45% to 65 %.

2. Experimental

The steel used was a AISI 4340 type steel collected locally in the form of a bar. The chemical composition of the steel is given in Table 1. Cylindrical bars of 10 mm in diameter and 120 mm long were cut and first subject to heat treatment in order to obtain the desired ferrite-bainite structures. This heat treatment consisted of the following sequential steps: (a) austenitizing the steel at 1100 °C for 1 h, (b) performing intercritrical annealing at 730 °C while adjusting the annealing durations, in order to obtain samples with various V_f values, (c) soaking in a salt bath at 350 °C for 40 min and finally (d) cooling in air.

Table 1. Chemical composition of the investigated steel

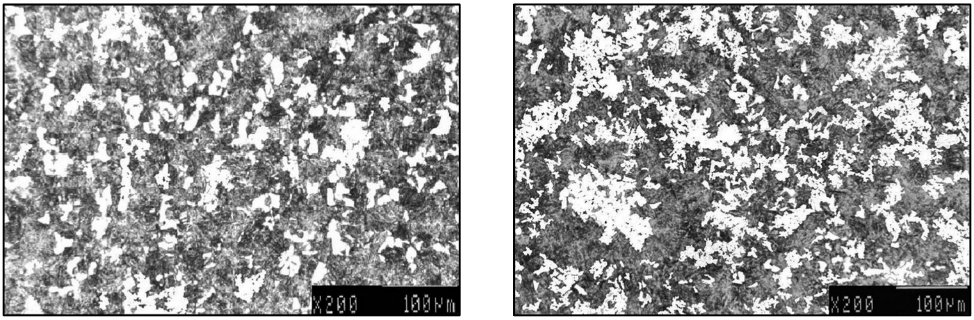
Element	Content [wt. %]
C	0.442
Si	0.292
Ni	1.840
Mo	0.246
Mn	0.722
P	0.024
Al	0.027
Cu	0.262
S	0.010
Cr	0.782
Co	0.012
V	0.002
Fe	Base

Samples for microstructural studies were fabricated and etched with 2% Nital solution and then examined under an optical microscope. Volume fractions of the phases were measured by an image analyzer. Tensile specimens were fabricated with a gauge length of 36 mm. Tensile tests were carried out at room temperature using an Instron tensile machine with a cross head speed of 1 mm/min (strain rate of 4.6×10^{-4} 1/s). The relationship between the ferrite volume fraction and the deformation mechanism was predicted using tensile test data and the Hollomon equation. Finally, the fracture surfaces of the specimens were studied using a Philips XL30 scanning electron microscope.

3. Results and discussion

3.1. Microstructure

Ferrite-bainite dual phase steels were fabricated by isothermal treatment in the bainitic transformation range. Transformation temperatures were selected based on the calculated Ac1 and Ac3 transformation temperatures and martensitic start temperatures (Ms) from the empirical formula given in [18]. The Ac1, Ac3 and the Ms Transformation temperatures for the selected steel were found to be 710, 770 and 285 °C, respectively.



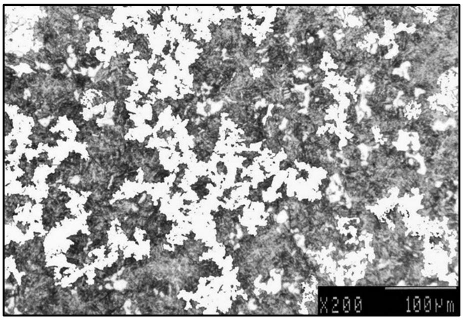


Fig. 1. Micrographs of steels with various V_f: a) 45.3 %, b) 54.9 %, c) 63.7 %

Light micrographs of steels with various V_f are shown in Fig. 1. The ferrite volume fractions of dual phase microstructures produced by intercritical annealing at 730 °C at various holding times of 80,120, 150 min are 0.453, 0.549 and 0.637, respectively.

3.2. Tensile properties

Engineering stress–strain curves for ferrite-bainite dual phase steels exhibited continuous yielding behaviour in the studied range of the ferrite volume fractions. The continuous yielding behaviour of ferrite–martensite dual phase steels has been attributed to the presence of unpinned dislocations introduced into ferrite by plastic deformation during the formation of martensite from austenite [19, 20].

The reason for the occurrence of continuous yielding in ferrite-bainite dual phase steels is not straightforward. Barbacki [21] reported that continuous yielding occurs in ferrite-bainite dual phase steels. Bhadeshia [22], however, mentioned that one may get either continuous or discontinuous yielding in ferrite-bainite dual phase steels, depending on the nature of the system. The factors which govern discontinuous yielding in steels are [20, 23, 24]: (i) low mobile dislocation density of the order of 10^2–10^4 cm^{-2} prior to deformation, (ii) a rapid rise in the number of dislocations that occur during deformation and (iii) a strong dependence of the dislocation rate on the applied stress. The amount and type of the harder constituent in a dual phase steel control the dislocation density, whereas the number of dislocations and the change in the dislocation rate depend on the morphology and the chemistry of the ferrite phase.

In ferrite-bainite dual phase steels, a considerable number of dislocations can be generated in ferrite by the transformation of austenite to bainite; therefore, to achieve continuous yielding in ferrite-bainite dual phase steels, the amount of bainite has to be increased to achieve a high dislocation density in ferrite. Interestingly, Barbacki [21] reported that the majority of dislocations produced during bainitic transformation are mobile in nature. Therefore, the observed continuous yielding behaviour of this dual phase steel may be attributed to the possibility that a high density of mobile dislocations is produced due to the higher volume fraction of bainite in the microstructures of the steels under consideration.

The tensile stress–strain curves have been analyzed to obtain estimations for the yield strength (YS), ultimate tensile strength (UTS), uniform elongation (UEL) and total elongation (TEL) from the tested specimens. The dependences of strengths and elongation of the investigated steel on the volume fraction of ferrite are shown in Figs. 2 and 3.

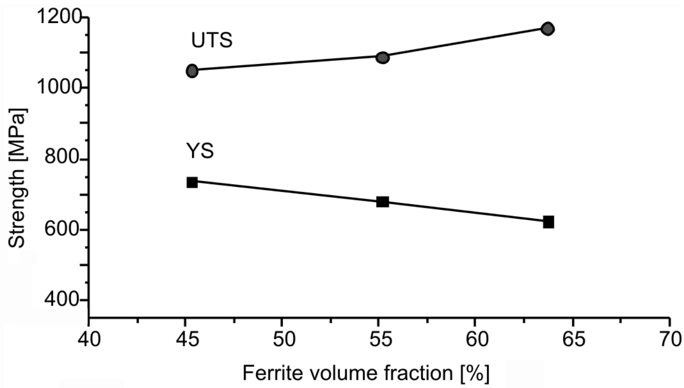


Fig. 2. Effect of the ferrite volume fraction
on the yield strength and the ultimate tensile strength

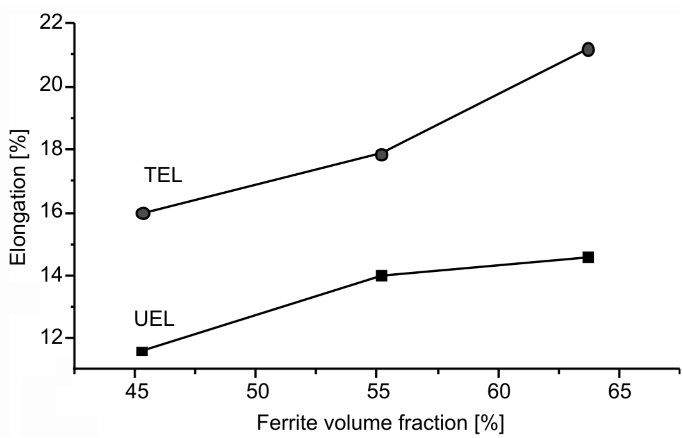


Fig. 3. Effect of ferrite volume fraction on ductility

The variation of the yield strength with the increase in the amount of bainite (ranging between 0.45 and 0.64 vol. %) is linear. It has been demonstrated [16] that as the ferrite volume fraction yield increases, the ultimate tensile strength decreases, while elongation increases (for $V_f < 0.34$). In this study, a different effect of V_f on ultimate tensile strength was noted. With increasing V_f in the considered range, yield strength decreases while elongation and UTS both increase.

The linear dependence of the yield strength on the volume fraction of the harder constituents in DP steels is often considered fortuitous, because the strength of bainite depends on the carbon content. The nonlinear dependence of strength of dual phase steel on the volume fraction of martensite in martensitic DP steels has also been indicated by some authors [25–28]. They reported that the non-linear increase of the strength with the volume fraction of martensite depends on the strength of martensite, which varies with its carbon content.

In addition, it is to be borne in mind that carbon partitioning between the constituents during processing of these steels would also affect the nature of the constituents, leading to alteration of their strength values. Thus, the overall strength of DP steel depends on: (i) the relative amount of the phases and (ii) their strength. Studies related to strength versus amount of ferrite in our earlier investigation [16] are limited to higher volume fractions of bainite. The observed variation of the ultimate tensile strength with the volume fraction of bainite in the investigated DP steel containing 45–63% of ferrite is dissimilar with high and low bainite DP steels. The ductility of the investigated steels (with 45–63 vol. % of ferrite) has been considered in terms of the elongation percentage, as shown in Fig. 3.

Elongation increases with the increase in the ferrite volume fraction. The variation of the ductility with the volume fraction of ferrite shows a maximum elongation (for ca. 65 vol. % of ferrite). It seems that above ca. 55 vol. % of ferrite the rate of UEL increasing has been reduced. In total, the variation of the strength and the ductility of DP steels are governed by three major factors: (a) the mean intercept lengths of the phases/constituents, (b) internal stresses in the phases/constituents and their influence on the composite structure, and (c) the strength and ductility of the individual phases/constituents governed by the compositional variation.

The magnitude of strain hardening stress, which is the difference between the UTS and YS, i.e.

$$\Delta\sigma = \sigma_{\text{uts}} - \sigma_{\text{ys}}$$

is plotted in dependence of the ferrite volume fraction (Fig. 4). It is seen that $\Delta\sigma$ increases as V_f increases.

For F-M DP steels, the dependence of the tensile strength on the hard phase content has been empirically modelled [29–31] and formulated based on the rule of mixtures

$$\sigma_t = \sigma_2(1 - V_f) + \sigma_1 V_f \quad (1)$$

where σ_1 and σ_2 are the tensile strengths of the ferrite and the hard phases, respectively. If σ_1 and σ_2 are assumed to be invariant with respect to the amount, nature, and morphology of the respective phases, Eq. (1) predicts a linear relation between σ_t and V_f. Experimental results obtained in the present work appear to agree with the suggested empirical expression of Byun and Kim, [30] up to $V_f = 45.3$ vol. %. However, the experimental results are inconsistent with the predicted trends for $V_f > 45.3$ vol. %. Beyond this level of V_f, the experimental results show that the tensile strength increases with the increase in the ferrite content, whereas the models predict the tensile strength to decrease.

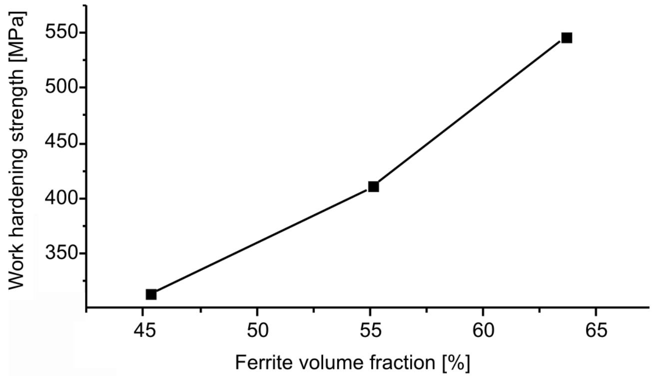


Fig. 4. Strain hardening stress vs. V_f

Furthermore, if σ_1 and σ_2 denote the YS of ferrite and bainite, respectively, and are assumed to be invariant with respect to the amount, nature, and morphology of the respective phases, the experimental results obtained in the present work appear to agree with the rules of mixtures (Eq. (1)). The YS decreases monotonically with the ferrite volume fraction in an approximately linear manner.

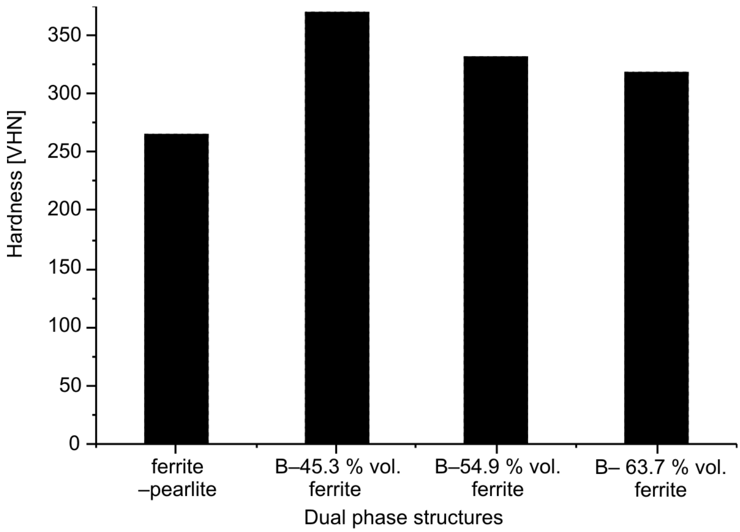


Fig. 5. Hardness [MPa] vs. YS for different dual phase structures

The Vickers hardness of different studied microstructures is shown in Fig. 5. According to the data in this figure, the variation in the hardness of dual phase steels is a good indication of the bainite content that existed in the microstructure. The Vickers hardness of the specimens (after intercritical annealing) bears extremely good polynomial correlation with the experimental yield strength as follows:

$$\mathrm{VHN} = 0.0036\mathrm{YS}^2 - 4.3896\mathrm{YS} + 1667.5 \qquad \mathrm{VHN\ and\ YS\ [MPa]}$$

3.3. Strain hardening behaviour. Hollomon analysis

Strain hardening exponents n of the investigated dual phase steels were determined using Hollomon's equation, as per ASTM standard E-646-98 [32]. These values are estimated from the slope of the lg–lg plots of the true stress σ vs. the true plastic strain ε data obtained from the tensile tests. Some typical representative plots of $\ln\sigma$–$\ln\varepsilon$ for the FBDP steels are shown in Fig. 6, which appear to deviate from linearity, though the linear regression coefficients (r^2) associated with the calculation of n are in the range of 0.965–0.997.

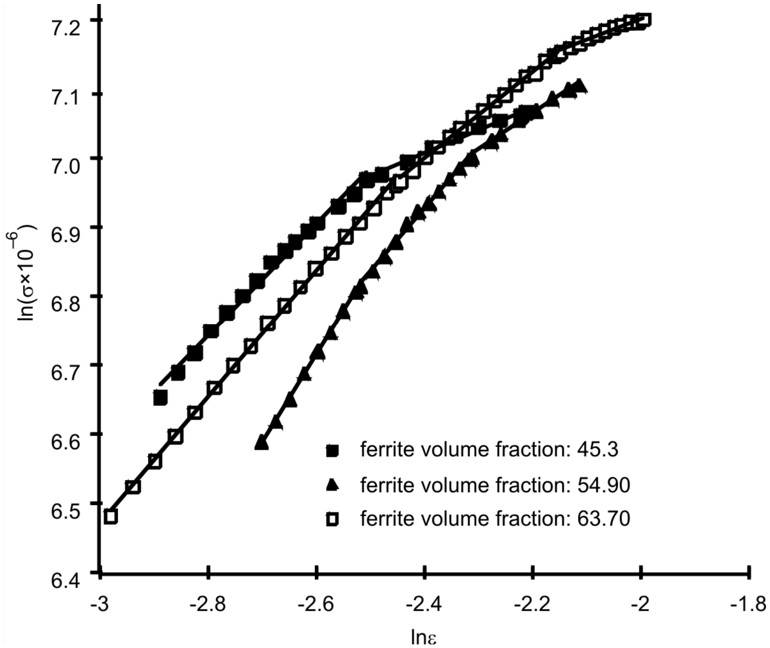


Fig. 6. $\ln\sigma$–$ln\varepsilon$ plots of investigated steel with various V_f

For these steels the dependence of $\ln\sigma$ on $\ln\varepsilon$ is nonlinear. This means that only one n value cannot describe the flow and work hardening behaviour of these materials. Some researchers explained that dual phase steels show two stage requiring two work hardening indices [16, 17, 28, 33–36]. Other authors showed three hardening stages for some dual phase steels, such that each stage exhibits structural evolutions during deformation [2, 37–39]. The existence of different work hardening stages in various DP steels has been related to different activated deformation mechanisms at strain range corresponding to each stage. These mechanisms are a sequence of phase deformations (homogeneous or heterogeneous), minimum plastic incompatibility and possible phase transformation during deformation such as transformation of retained austenite to martensite and dynamic recovery [2, 16, 17, 28, 30, 33–38].

According to the results for the steel with V_f of ca. 45.3 %, two stages of work hardening were found [16, 17]. The first stage has a high strain hardening exponent and the second stage has a low one. These results are in agreement with the results of previous works on work hardening behaviour of ferrite–martensite dual phase steels [33–36]. According to these works, the first stage is associated with plastic deformation of the ferrite matrix and the second one with plastic deformation of both ferrite and martensite. However, Lian et al. [36] according to their theoretical and experimental results on work hardening behaviour of ferrite-martensite DP steels having different amounts of martensite concluded that the first stage of work hardening in steels with $V_m > 50\%$, martensite first deforms elastically and then deforms partly elastically and partly plastically. The second stage of work hardening is associated with plastic deformation of both ferrite and martensite.

In the present work, no TEM analysis was done on the deformation behaviour of bainite, but it seems that the model of Lian et al. is applicable to the present work, since the volume fraction of bainite is higher than 50 vol. %. The deformation of hard phase, martensite or bainite, depends on the strength difference between two phases. A higher strength difference corresponds to elastic deformation and a lower one corresponds to plastic deformation of the hard phase. The yield stress of the second phase (bainite) depends on its carbon content. The higher the carbon content, the higher the strength of the second phase is. The carbon content of the second phase decreases as the volume fraction of the second phase increases [39]. By applying the rule of mixtures, the carbon content of hard phase, bainite may be determined.

In the present work, for steel with $V_f > 54.9$ %, three-stage work hardening was found. The most probable explanation for the results is as follows:

Stage I is due to homogeneous deformation of ferrite. The rate of work hardening is high because undissolved carbide particles impede the glide of dislocations in the ferrite phase. The possibility of martensite deformation is not ruled out. Stage II is due to a condition of going through and minimum plastic incompatibility, resulting in lower internal stresses and, thus, enhancing the easy flow of dislocations. Stage III consists of simultaneous deformation of ferrite and martensite associated with dynamic recovery.

Specific evidence has not been obtained to support the above hypothesis; however, some experimental observations further support this view. First, the slope of the $\lg\sigma$–$\lg\varepsilon$ plots, for stage I, is lower for specimens containing higher amounts of ferrite. This observation implies a higher work hardening rate in stage I for samples containing more ferrite than for those containing less ferrite. The correspondence between lower work-hardening rates and higher V_b is attributed to an ease of the dislocation flow, owing to the absence of barriers, such as the undissolved carbide particles. Secondly, onset strains of stage III work hardening increase with the increase in the ferrite volume fraction. This corresponds to harder deformation of bainite which increasing ferrite volume fraction (i.e., carbon content of bainite) which need much strain to deform in the third stage. The occurrence of stage II may be due to dynamic changes of internal stresses during plastic deformation. However, no conclusive support could be obtained to satisfactorily explain this stage of deformation

3.4. Fractography

Figure 7 shows fracture surfaces of tensile tested specimens having a 45.3% and 63.70% volume fraction of ferrite. It was seen that the tensile fracture mechanism of

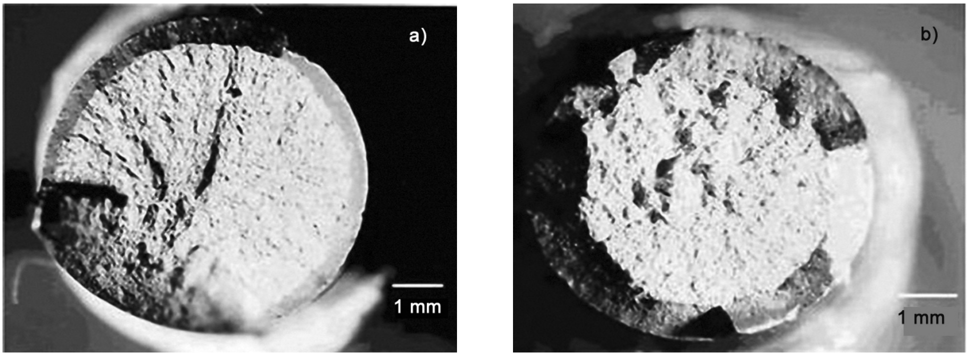


Fig. 7. Macrofracture surfaces of tensile tested specimens with:
a) 45.3% and b) 63.70% volume fractions of ferrite

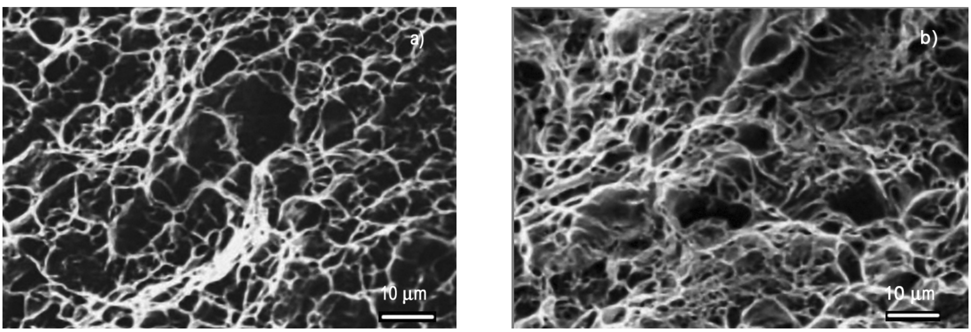


Fig. 8. SEM photographs of the central section of fracture surfaces
of tested specimens with: a) 45.3% and b) 63.70% volume fractions of ferrite

these steels is the classic “cup and cone” type fracture at room temperature. Also a scanning electron microscope photograph of the central section of the fracture surfaces are shown in Fig. 8. The fracture surfaces of the studied DP steels reveal the presence of dimples, indicating a typical ductile mode of fracture. According to Džupon et al. [40], the fracture surfaces of ferrite-martensite DP steel with different constituents volume fractions (20–88 vol. % of martensite) after uniaxial tension loading had ductile dimple morphology, with statistically distributed dimples of greater sizes and depths. As V_m grows, the occurrence of deeper and greater pits becomes more frequent. Similar to ferrite-martensite DP steels, samples having various bainite contents exhibited dimples of various sizes; as the volume fraction of ferrite increases, the dimple size decreases. The decrease in the dimple size is attributed to a larger number of void initiations in FBDP steels having higher ferrite content.

4. Conclusions

Ferrite-bainite dual phase steels with different ferrite volume fractions (from 45 vol. % to 65 vol. %), were produced using appropriate heat treatment, and were tensile tested at room temperature. The results are summarized as follows:

In ferrite-bainite DP steels, the yield strength (YS) increases monotonically with the ferrite volume fraction but the ultimate tensile strength (UTS) does not. UTS increases only when the ferrite volume fraction V_f increases above 55 vol. %.

The specimens intercritically annealed for 2.5 h and having 63.7 vol. % of ferrite exhibited the best combination of work hardening and ductility. Two or three Hollomon equations are sufficient to describe the flow behaviour of this DP steel adequately, and it was ascertained that as V_f increases, the work hardening takes place in three stages.

The Vickers hardness of DP steels decreased with the increase in the ferrite volume fraction. It is observed that the Vickers hardness of the specimens (after intercritical annealing) bears extremely good polynomial correlation with the experimental yield strength.

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