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Modelling the flow behaviour of dual-phase steels with different martensite volume fractions by finite element method

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Abstract

Dual-phase (DP) steels have a composite-type microstructure consisting mainly of hard martensite islands embedded in a soft ferrite matrix. DP steels exhibit a characteristic combination of high strength, high work hardening rate and good ductility. Mechanical behaviour of DP steels is closely related to their microstructures. Hence, it is necessary to take into account their microstructural parameters in any attempt to estimate their flow behaviour. In this study, the flow curves of low carbon DP steels with 26.4 and 52% martensite produced by intercritical annealing processes at different temperatures were calculated using the finite element method (FEM). According to the results of microscopical observations of steel microstructures, martensite islands were assumed in the model to be spherical in shape. Moreover, in agreement with the experimental results in the literature clearly showing the possibility of martensite plastic deformation in similar steels during straining when its volume fraction is greater than about 30%, the plasticity of martensite islands in the steel microstructures was taken into account in the model by using their experimentally obtained stress-strain relations as a function of their estimated carbon contents. Having estimated the stress-strain behaviour of the ferrite phase in all steel samples using the microstructural parameters corresponding to the starting ferrite+pearlite steel, the flow curves of different DP steel samples with elastic martensite (in low martensite content steels) and elasto-plastic martensite (in high martensite content samples) were calculated. The calculated stress-strain curves exhibited reasonable agreements with the experimental stress-strain curves obtained from the tensile tests.

Introduction

Dual phase (DP) steels having a microstructure consisting of hard martensite islands within a ferrite matrix have received considerable attention due to their high tensile to yield strength ratio, continuous yielding behavior, high work hardening rate and good ductility. These characteristic mechanical properties of DP steels result in a weight reduction at a reasonable strength level and a superior formability when compared with the high strength low alloy (HSLA) steels [1-3].

Since mechanical properties of materials are closely related to their microstructures, attempts have been made in the past few decades in order to control as well as to modify the microstructure of materials with the final goal of the improvement of their properties. The key element in this process is to establish a mathematical model to predict and/or to estimate the microstructural evolution during manufacturing processes considering the fact that it has a significant effect on the final mechanical properties of the product.

There are several reports on the evolution of the mechanical properties of materials from their microstructure. These reports include regression method according to the chemical composition of steels [4], secant method using the Eshelby model [3,5], and finite element method (FEM) [1,2,6]. Among these modelling approaches, FEM has the advantage of taking into account the morphologies of phases as close as possible to the actual microstructures.

In this study, an attempt has been made to predict the flow curves of two low carbon DP steels using the finite element approach in which microstructural unit cells were considered with the help of the quantitative microstructural analysis. To do this, mechanical properties of the martensite phase with 0.1%C were obtained experimentally, whereas those of the martensitic steel having 0.3%C and the ferrite phase (0.06%C and containing 8% pearlite) were estimated based on the experimental results in the literature [6,7]. According to Gladman et al[8], the addition of 10% pearlite to a ferritic steel microstructure has an insignificant effect on the strength of the steel. The stress-strain curves of different DP steels containing different martensite volume fractions were estimated by finite element analysis, and then compared with the experimental curves. The possibility of martensite plasticity during straining was also evaluated in DP steel samples containing different amounts of martensite phase.

Experimental Procedure

Two different steels containing 0.06 and 0.09 weight percent carbon were used to produce DP steel samples. The chemical compositions of these steels are given in Table 1. Steel samples were first heated to the intercritical temperatures of 795 ºC and 761 ºC, respectively, held at these temperatures for 15 minutes, and then quenched in a brine solution (tap water-10% NaCl). After the intercritical heat treatment, steel samples were polished following a detailed procedure recommended by Buehler Ltd. [7]. For the optical microscopic examinations, the polished samples were etched in an aqueous solution prepared by adding 10 grams sodium metabisulfide into 100 mL distilled water. The quantitative microstructural measurements were conducted using the Clemex image analyzing software. The average martensite volume fractions in DP steel samples were determined using 20 to 30 images taken from different locations in the steel microstructures.

Table 1. Chemical compositions of the investigated steels used as starting materials

Element	C	Mn	Si	Mo	P	S
Wt. %	0.06	1.86	0.07	0.15	0.012	0.002
Wt. %	0.09	0.45	0.12	-	0.017	0.02
Wt. %	0.1	1	0.013	0.001	0.007	0.007

The intercritical temperature, martensite volume fraction and its carbon content in all DP steel samples are summarized in Table 2. In order to obtain the stress-strain curve of martensite phase having 0.1wt.% C, a steel sample with 0.1wt.% carbon was heated to 950ºC and held at this temperature for 5 minutes, then quenched in the brine solution. The resulting steel was examined to be a martensitic steel with 0.1wt.% carbon.

Since austenite to martensite phase transformation is diffusionless, it is reasonable to assume that the carbon content of martensite phase at room temperature to be the same as that in the austenite phase at the intercritical temperature. Therefore, the carbon content of martensite in DP steel samples can be estimated using the equilibrium Fe-C phase diagram and the temperature at which the intercritical annealing has occurred.

Table 2. The volume fraction of martensite and its carbon content in two different DP steel samples intercritically annealed at the specified temperatures

Samples	Martensite volume fraction (%)	Martensite Carbon Content (wt.%)	Intercritical temperature (°C
DP-1	26.4	0.3	761
DP-2	52	0.1	795

Tensile specimens with the length and width of 25 mm and 6 mm, respectively, were machined from the intercritically annealed-quenched DP steel samples. The tensile loading direction was parallel to the rolling direction of the starting sheet material. Tensile tests were conducted using Zwick Z250 screw driven universal tensile testing machine at room temperature and a constant strain rate of approximately 2×10^{-3} s^{-1}.

An axisymmetric cell with a uniformly aligned particles distribution was considered for the finite element modelling of flow curve of the DP steel samples. Axisymmetric cell models have been widely used for the prediction of the flow behaviour of particulate metal matrix composites [9,10]. This approach has recently been used in estimating the flow curves of dual-phase steels [1,2]. According to the results of comprehensive microstructural examinations of DP steels, when the martensite volume fraction is lower than around 30% the martensite islands can be viewed as separated spherical particles embedded in a ferrite matrix, while, when the martensite volume fraction is high (greater than 30%), ferrite grains can be approximated as spherical particles embedded in the martensite matrix.

Since the martensite islands in the DP steel microstructures are assumed to be spherical in shape, a finite element mesh was selected as shown in Figure 1 in which, due to the symmetry, only one quarter of the cell was considered for the modelling. The FEM analysis was performed using ABAQUS general purpose software. Four-node axisymmetric reduced elements (CAX4r) were used for the discretization of the structure.

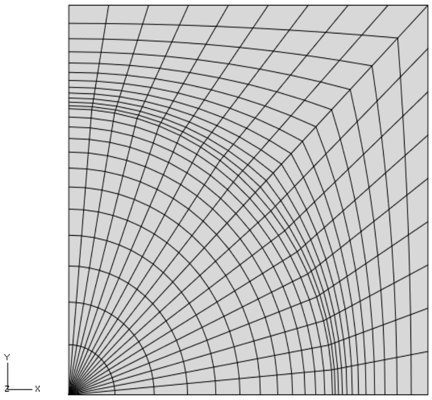

Figure 1. One quarter of the cell as a representative of the whole FEM mesh considered for the microstructures of the investigated DP steels.

The displacement was applied on the top boundary of the cell in *y*-axis, and the bottom and right-hand side boundaries were considered to be symmetric axes. The left-hand side boundary was assumed to be free to move in any arbitrary direction. The volume fraction of the particles in the microstructure, V_m , was calculated using the following equation:

$$V_m = \frac{2}{3}\frac{a^3}{L^3}$$

where *a* is the radius of spherical part of the cell and *L* is half of the length of the cell. V_m is the volume fraction of the spherical to cylindrical sections of the cell. Accordingly, when the martensite content is low (less than 30%*)* V_m is the volume fraction of martensite, whereas it represents the ferrite volume fraction when the martensite volume fraction is high (greater than 30%).

For the modelling purpose in this investigation, both phases were considered to be elasto-plastic solids with $E = 210$ GPa and $\nu = 0.3$ [1-3].

Results and discussion

The flow curves of both the ferrite and martensite phases were used for calculating the flow curves of DP steel samples. Ferrite phase was assumed to be the same in the microstructures of the investigated DP steels. According to the results given Table 1, the martensite phases in DP-1 and DP-2 steels contain approximately 0.3wt.% and 0.1wt.% carbon, respectively. Figure 2 shows the stress-strain curves of the ferritic steel, and the fully martensitic steels with 0.3%C and 0.1% carbon. As can be seen in this figure, both the martensitic steels have exhibited a limited amount of plasticity during tensile straining. The experimental and calculated stress-strain curves of DP steels with 26.4% and 52% martensite are shown in Figures 3-a and 3-b, respectively. The results in Figure 3-a show that there is a good agreement between the calculated stress-strain curve of DP steel with 26.4% martensite and that obtained from the tensile test. For the case of DP steel containing 52% martensite (Figure 3-b), there is an excellent agreement between the curves up to the applied strain of 5%. However, the flow stress of the steel has been slightly overestimated by FEM still representing a relatively reasonable agreement with the experimental results.

As it can be clearly observed in Figure 3, the flow stress of both low and high martensite content DP steels has been well estimated by FEM with a relatively small discrepancy with the experimental results. In the previous investigation on modelling the stress-strain response of 0.06wt.% carbon DP steel as a function of the martensite content, [6], the modified Eshelby model has been successfully employed for the prediction of the flow behaviour of DP steel with less than 30% martensite. However, for the case of DP steels with martensite volume fractions greater than 30% the Eshelby model has highly overestimated their corresponding flow stresses, mainly due to the significant deviation in the assumptions made in the modified model from those of the original Eshelby approach.

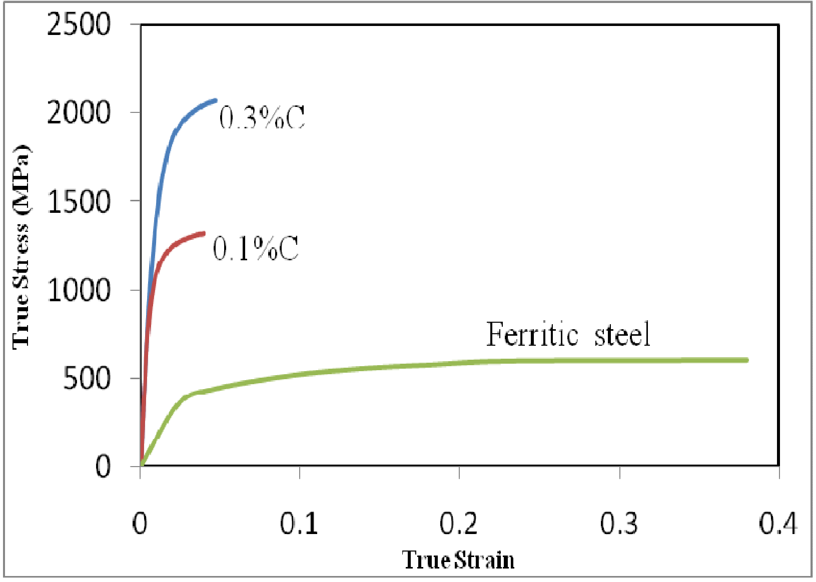

Figure 2. The stress-strain curves of 100% martensite steels with different carbon concentrations and ferritic steel.

Figure 4 shows the calculated equivalent plastic strain (PEEQ) at the maximum far field strain applied to the specimen. As it can be clearly observed in this figure, the strain distribution in both DP

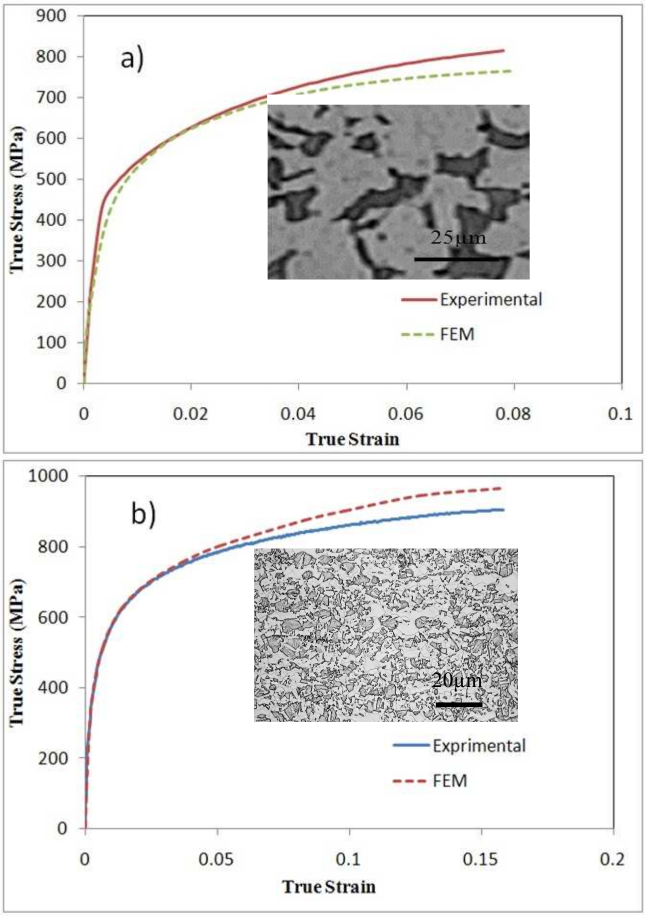

Figure 3. Experimental and calculated flow curves together with microstructure of DP steel samples with 26.4% martensite (a), and 52% martensite (b).

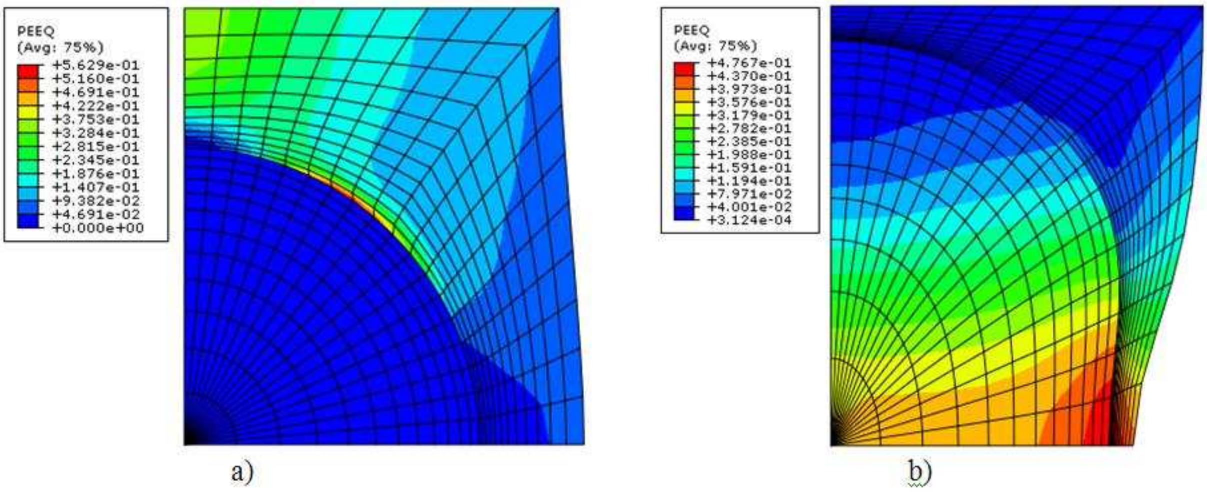

Figure 4. Two-dimensional representation of the equivalent plastic strain (PEEQ) distribution at the maximum strain applied to the sample; (a): DP steel with 26.4% martensite, and (b): DP steel with 52% martensite.

steels are quite heterogeneous, which is consistent with the experimental observations of Shen et al. [12], and Rashid and Cprek [13]. Furthermore, Figure 4-a shows that the martensite phase in DP steel with 26.4% martensite has remained elastic during the whole deformation regime, whereas for the steel containing 52% martensite a considerable plastic deformation has occurred within the martensite phase. This series of modelling results is also in a good agreement with the previous experimental findings for the case of DP steel microstructures [3,12].

Conclusion

In this study, finite element modelling approach was utilized for prediction of the stress-strain response of two low carbon DP steels containing 26.4% and 52% martensite. Using this model, it was possible to estimate the flow behaviour of these steels with the help of flow curves of both the constituent phases, i.e. ferrite and martensite. The predicted flow curves were in good agreement with the flow curves obtained from the tensile tests.

The strain distribution between martensite and ferrite phases in DP steel microstructures during deformation was inhomogeneous mainly due to the significant difference between their strength and plasticity behaviour.

The results in this investigation clearly showed that the martensite phase in DP steel with lower martensite content (26.4%) remains elastic during almost the entire deformation regime whereas the martensite phase in DP steel containing higher amount of martensite (52%) shows a considerable plasticity when the steel is under tensile loading.

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