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PRODUCTION AND TENSILE CURVE PREDICTION OF DUAL PHASE STEELS BY MICRO-MECHANICAL MODELING

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Abstract-Dual phase steels are used in majority of the automobile applications due to their high strength-to-weight ratio. These steels have been produced by using various processes to achieve better and better properties. In this context, an extremely limited work has been reported for their production using lean chemistry approach. In the present work, a dual phase steel was produced with controlled cooling and using lean chemistry. A variable volume fraction of martensite could be achieved in ferrite through annealing in an annealing simulator. Tensile testing of the produced steel with different martensite volume fractions (MVF) was done, by which, various combinations of strength and ductility could be achieved. Micro-mechanical modeling to obtain/predict the tensile curves was also done for the steel. The true stress-strain curves obtained through actual tensile experiments closely matched with those predicted by the micro-mechanical modeling.
Keywords:- Dual phase steels; Micro-mechanical modeling; Tensile curves; Martensite volume fraction

1. INTRODUCTION

The automotive industry aims at the production of vehicles with low weight, fulfilling demanding requirements of safety, reduced fuel consumption and lesser emission of harmful exhaust gases. In order to meet these demands, improvements in the known materials and invention of newer materials with high strength-to-weight ratio and better suitability for metal forming operations are under progress [1]. In this regards, dual phase (DP)-steels are the promising candidate materials to be used in the automotive industry.Microstructure of dual phase steels is composed of soft ferrite matrix and 10–40% of hard mastensite. This type of microstructure allows achieving an ultimate tensile strength in the range of 500–1200 MPa. The mechanical properties of dual phase steels are controlled by metallurgical factors, such as the volume fractions of the martensitic and ferritic phases, the carbon content of martensitic phase, the grain size of the martensite and ferrite, and the individual resistances of both martensitic and ferritic phases. Furthermore, the resistance of these phases, is also affected by the chemical composition of steel [2].

DP-type sheets can be produced by the classical heat treatment, which consists of their austenitizing at a temperature slightly higher than A_{c1}(Lower critical temperature) followed by water quenching. Alternatively an energy-saving technology of the thermo mechanical treatment, integrating hot-rolling in the austenitic field or $\alpha + \gamma$ region with direct cooling could be employed [3-5].It has been concluded from the literature that only a limited work has been done to produce the bainite/ferrite or martensite/ ferrite microstructure of dual phase steels by controlled cooling approach. However, mechanical properties obtained by lattermethod are far better than all the other methods, microstructural due to, grain refinement e and proper volume fraction of phases [6]. Also, the chemistry chosen by them to produce DP steels was complex, which includes high cost alloying elements viz; niobium, vanadium, titanium. [2-5].

Material characterization is an important tool to describe and establishthe mechanical and metallurgical properties of materials,which are developed byselecting optimum material chemistries and processes suitable to obtain microstructures. The usual approach of achieving these objectives through experimental techniques is generally costly and time consuming. To overcome these constraints of experimental approaches, several modeling approaches are generally developed. In the current work also, amicro-modeling approach has been developed, which may help in predicting the material behavior without extensive experimental investigation. The proposed model is based on the microstructural characteristics of the given material [7-12]. Moreover, the dual steel was produced from a lean chemistry approach through controlled cooling to obtaining various combinations of strength and ductility, by which we could achieve different martensite volume fractions with respect to annealing temperature. Also, the micro-mechanical modeling to obtain/predict the tensile curves was done for the developed steels.

2. METHODOLOGY

The starting material was a normalised DP steel sheet of 1.0 mm thickness having a chemical composition as shown in Table 1.Specimens of the as-received steel were prepared for microstructural examination using standard metallographic techniques, which include mounting, planar grinding, rough polishing, final polishing and etching. Nital, a solution of HNO_3 (3%) in ethanol was used as the etchant to etch the surface of the specimens. Micrographs were recorded with an optical microscope atdifferent magnifications(100X, 200X, 500X, and 1000X). Next, annealing experiments were conducted under

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a process parameter set; adopted from literature [6] which are reproduced in Table 2. For annealing, samples to be treated in the annealing simulator were prepared which were of the standard dog-bone shape with 35 mm gauge length.

Table 1: Chemical composition of the as-received DP-steel

Element	C	Mn	Si	Fe
% wt.	0.11	1.8	0.325	Balance

The samples were subjected to isothermal annealing in the temperature range, Ac_1–Ac_3(lower critical temperature to upper critical temperature)(685 ℃–850 ℃) at different inter-critical temperatures (from 7500 ℃ to 850 ℃) and held for 3 minutes followed by controlled cooling.Schematic for the heat treatment is shown in Figure 1. The samples were directly cooled (at a rate more than critical cooling rate) to room temperature from the heat treatment temperature, which showed martensite/ ferrite microstructure. Heating chamber of the annealing simulatorwas charged with amixture of hydrogen and nitrogen gases even before loading the samples to provide protection against oxidation through a reducing environment.

Table 2. Annealing temperature, time and cooling rate conditions for DP-steel[6]

Sr. No.	Heating temp (℃)	Soaking time (min)	Cooling rate (℃ /s)
1	750	3	15
2	800	3	20
3	850	3	40

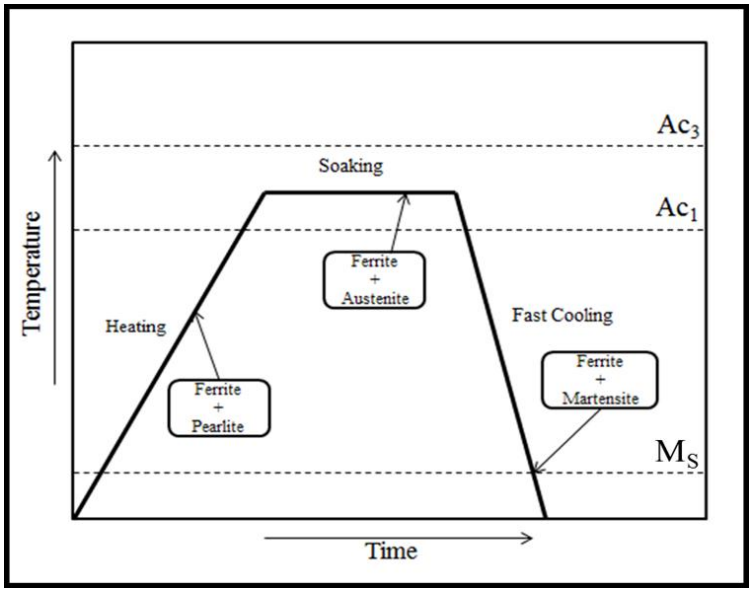

Fig. 1 Schematic for phase transformation during heating, holding and cooling of DP steels[13]

After heat treatment under various temperature-time conditions, microstructure of the samples was investigated by optical microscopy (Make: Leica DM2500 M; Lieca Microsystems, Wetzlar, Germany). Phase fraction of constituent phases was calculated using the software 'Image-J'.

Tensile tests were conducted (as per the ASTM standard E-8M) onall the samples at room temperature under displacement control at a strain rate of 1 x 10^{-3} s^{-1} using a tensile testing machine (Make: Instron 8862 System, Instron Engineering Corporation, Norwood, USA) of 100 kN capacity in the region of uniform elongation. Elongation was measured by an extensometer of 25mm gauge length.

2.1 Micro-Mechanical Modeling of Dual Phase Steels

Micro-mechanical model as reported by Alabbasi (2004) [10] has been used in the present work to predict the mechanical properties of DP steels developed in the present work. The tensile properties of the steel containing DP structure at various annealing temperatures were obtained through actual tensile experiments and were compared with micro-mechanical model predictions to validate the latter.

To apply this modeling approach, it was necessary to evaluatethe tensile properties of individual phases (i.e. ferrite and martensite) present in the given DP steel. For this, behavior of each of thephase was determined by achieving single phase in the steel (fully ferritic orfully martensitic structure separately). The single-phase steel was then tested in tension to obtain the characteristic tensile behavior of a specific phase. In this manner, the engineering stress-strain curves for ferrite phase and

martensite phase were obtained separately. These engineering stress-stress strain curves were thenconverted into true stress strain curves for ferrite and martensite. The conversion was done by using the formulae [10]:

$$\text{True Strain} = \ln\left(1 + \frac{\varepsilon}{100}\right) \quad (1)$$

$$\text{True Stress} = \sigma\left(1 + \frac{\varepsilon}{100}\right) \quad (2)$$

where, ε is engineering strain, σ is engineering stress.

3. RESULTS

The microstructure of the as-received steel having composition of DP-steel, typically comprises pro-eutectoid ferrite (88%) and pearlite (12%) with an average grain size of 15 μm (as calculated by linear intercept method).This steel has an ultimate tensile strength of 475 MPa, along with a yield strength of 350 MPa and % elongation of 33 %(Singh et al 2016).When the samples were annealed at 750 ℃ and cooled after 3 min of stipulated soaking, at a cooling rate of 30 ℃ /s, a dual phase structure consisting of ferrite and martensite, was observed as shown in Fig. 2a. The 'Image J' software detected volume fraction of martensite phase to be 15 %. When the samples were annealed at 800 ℃ and cooled after 3 min of stipulated soaking, at a cooling rate of 40 ℃ /s, another ferrite and martensite dual phase structure was observed as shown in Fig. 2b. In this case, volume fraction of martensite phase was found to be 20 %. Further, when the samples were annealed at 850 ℃ and cooled after 3 min of stipulated soaking, at a cooling rate of 60 ℃ /s, the observed dual phase structure is shown in Fig. 2c, with 37 % volume fraction of martensite phase,which is a significant amount for DP steels to get a very good combination of strength and ductility. It is anticipated that two major phenomena occur during the inter-critical annealing of theDP chemistry steel, viz; recrystallization of deformed ferrite grains and austenite formation. During heating and holding, some of the ferrite get recrystallized and pearlite started converting into austenite. During subsequent cooling, the ferrite and pearlite phases remain unchanged, whereas austenite transformed to fine grained martensite[14]. Increase in volume fraction of martensite may bedue to increase in volume fraction of austenite formation from pearlite during heating and holding (Fig. 1).

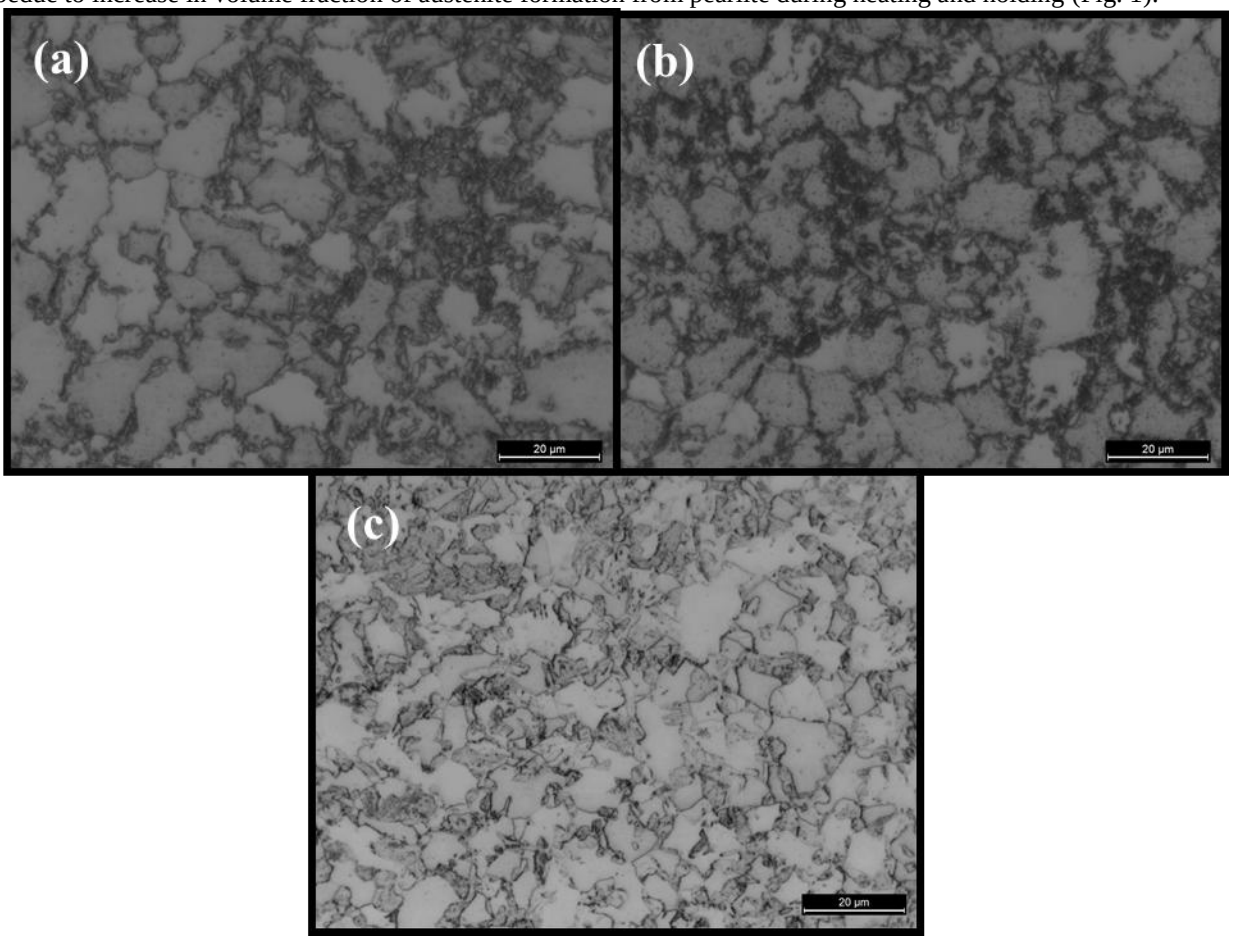

Fig2: Optical micrographs of DP-steel samples annealed in annealing simulator at various temperature and for 3 min soaking time (a) 700 ℃ (b) 800 ℃ (c) 850 ℃

The stress-strain curves for all the three samples annealed at 750, 800 and 850 C are shown in Fig. 3. For the sample annealed at 750 C, the yield stress (YS), ultimate tensile strength (UTS), and percent elongation were calculated as 260 MPa, 570 MPa and 30 % respectively. Whereas, for the sample annealed at 800 ℃, the yield stress (YS), ultimate tensile strength (UTS), and

percent total elongation were calculated as 290 MPa, 610 MPa and 23 % respectively.Furthermore, the sample annealed at 850 ℃, the yield stress (YS), ultimate tensile strength (UTS), and percent total elongation were calculated as 355 MPa, 705 MPa and 11 % respectively.Moreover, it can be noted that the annealed sample led to improvement in ultimate tensile strength but at the cost ofductility as the temperature of annealing increased from 750 ℃ to 850 ℃. This may attributed to the increase in martensite volume fractionand recrystallization of ferrite grains. Also, no yield point elongation was observed in the tensile curves, which might be due to hard phase (martensite) formation[15].

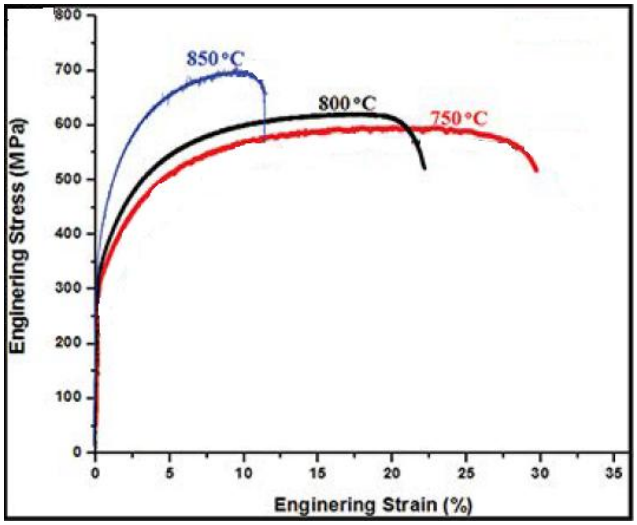

Fig 3:- Stress–strain curves for DP-steel specimens annealed at various temperature time conditions under controlled cooling.

3.1 Micro-mechanical modeling

Using Equations 1 and 2, the values of true strain and true stress were calculated for each of the phase. These values were used to plot the true stress-strain curves. From this true stress-strain curve, the range of stress-strain values corresponding to the strain hardening region was observed. The obtained values of true stress and true strain were converted to the 'ln' scale using OriginPro 8.0 software. These (true stress)' and (true strain)' values were plotted on ln-ln graph for the single-phase steel containing only ferrite as well as,only martensite separately are shown in Fig. 4a and 4b respectively. It may be noted here that the curves are being shown only for the strain hardening region as discussed above. These curves were now used to determine the strain hardening coefficient (n) for each phase by linear fitting of the curves (Figure 4 a–b). The strain hardening coefficient values (n) for ferrite and martensite phases were obtained as 0.21 (n_f) and 0.08 (n_m) respectively.

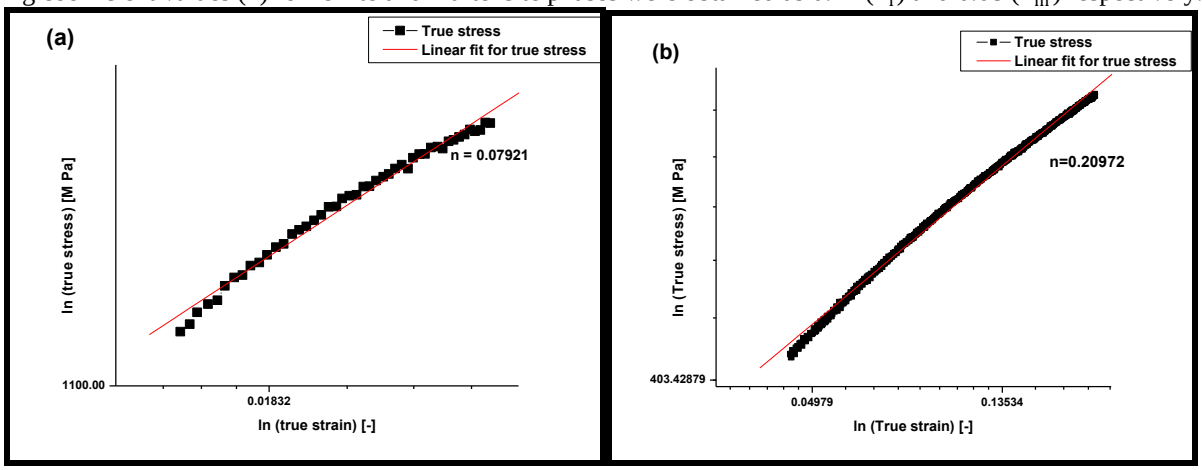

Fig. 4: ln-ln true stress-strain curves of DP-steel to obtain strain hardening exponent for (a) martensite and (b) ferrite

These strain hardening coefficient values were fitted to the power law relation as given by Alabbasi, (2004) [10], and represented as Equations 3 and 4. These equations were used to obtain the Hollomon strength coefficients (K_f and K_m) as shown below.

$$\sigma_f = K_f(\varepsilon_o + \varepsilon_f^p)^n{}_f \quad 3$$

$$\sigma_m = K_m(\varepsilon_o + \varepsilon_m^p)^n{}_m \quad 4$$

Where, K_m and $K_f$are the Holloman strength coefficients for martensite and ferrite respectively. ε_o is the strain corresponding to off-set yield strength and was taken as 0.002 in this work. n_m and $n_f$were taken as 0.08 and 0.21 respectively

(as calculated from Fig. 3a–b). ε_f^p and ε_m^p are uniform true strains for ferrite and martensite phases respectively (i.e. strains corresponding to ultimate tensile strengths). The values of ε_f^p and ε_m^p were obtained as 0.2517 and 0.039 respectively (according to the tensile experimental results for pure ferritic and pure martensitic structures)[6]. The ultimate true tensile stress values for martensite and ferrite phases were calculated as 1188.64 MPa (σ_m) and 595.14 MPa (σ_f) respectively. Using equations 4.3 and 4.4 and the vales of parameters as discussed above, K_m and K_f were calculated as 1530 MPa and 793 MPa respectively.

Finally, the rule of mixtures (Equation 5) as reported by Alabbasi (2004) [10] was used to calculate the composite true stress behavior of the DP steel containing known volume fractions of ferrite and martensite phases.

$$\sigma_c = V_m K_m (\varepsilon_o + \varepsilon_m^p)^n{}_m + (1 - V_m) K_m (\varepsilon_o + \varepsilon_f^p)^n{}_f \quad 5$$

where, σ_c is the true stress for the composite material (steel containing two phase), V_m is the volume fraction of martensite phase present in the composite material (i.e. the given steel).

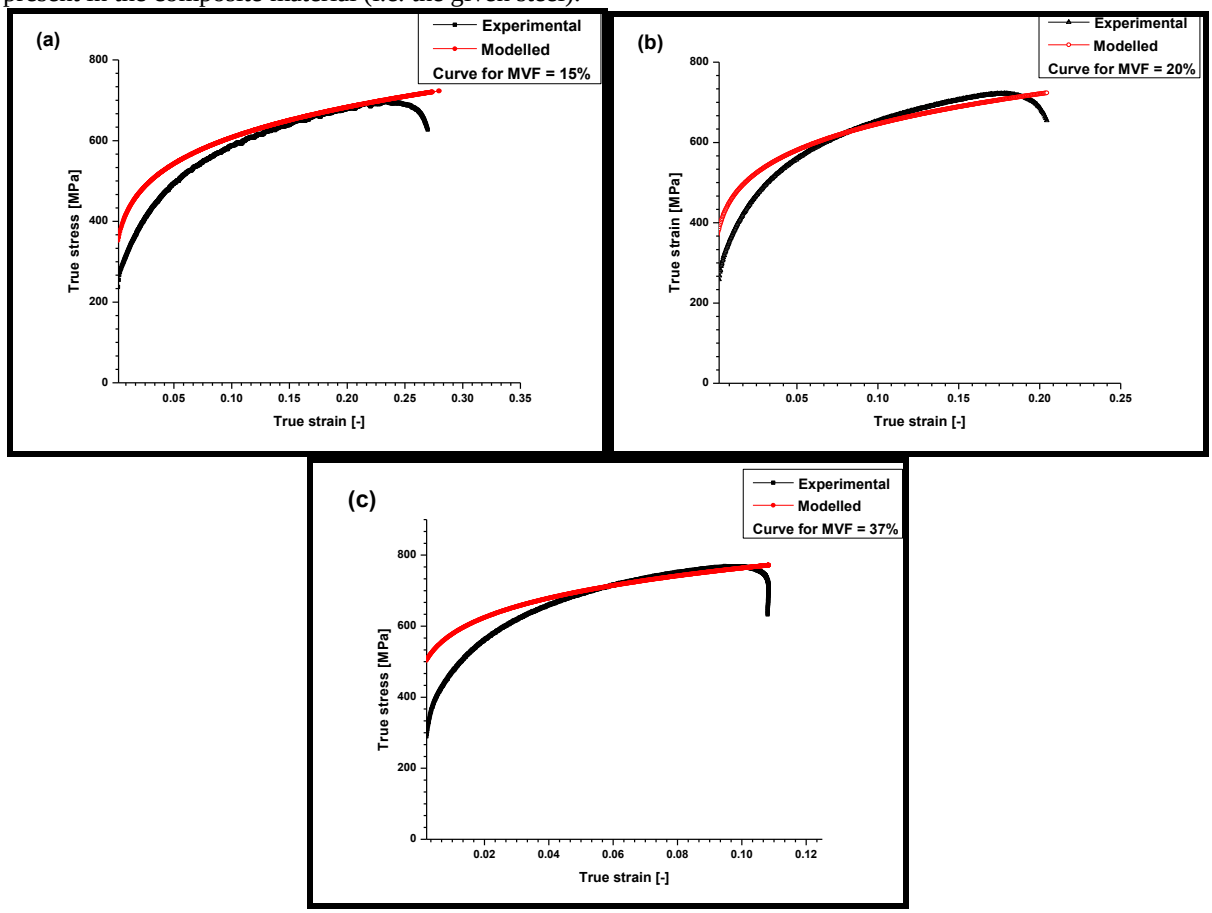

Fig. 5: Comparison of experimental and modelled true stress strain curves of DP-steel for different MVF (a) 15% (b) 20% (c) 37%. MVF = Martensite volume fraction

In this manner, for any given microstructure (with specific martensite fraction) in the DP steel, the true stress values for given strain values were calculated. Thus, the true stress-strain diagram based on micro-mechanical model was generated. This model based true stress-strain diagram was superimposed on the actual (experimental based) true stress-strain diagram for any given annealing condition (i.e. for any microstructure obtained through annealing experiments). Figure 5 (a–c) show the model based curves superimposed on the experimental true stress-strain curves for three different microstructures (containing martensite fraction of 15, 20, and 37% respectively) obtained (through route A at annealing temperatures of 750, 800, and 850 ℃ respectively) in the given steel.

It is observed from Fig. 5 that the true stress-strain curves obtained through micro-mechanical modelling match closely to the actual experimental true stress-strain curves for all the investigated dual phase microstructures in the given steel. Thus, this modelling technique (micro-mechanical modelling) can be utilized to predict the material behaviour without extensive experimental investigation only on the basis of microstructural characteristics.

4. CONCLUSIONS

A diverse range of strength-percent elongation combinations was obtained in the same lean chemistry steel through various heat treatment routes (570 MPa, 30% to 705 MPa, 11%). The true stress-strain curves of the steel containing DP structure at

various annealing temperatures obtained through actual tensile experiments closely matched with the true stress-strain curves predicted by micro-mechanical modelling. Thus, it is concluded that micro-mechanical modelling technique can be utilized to predict the material behaviour without the need for extensive experimental investigation.

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