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Real microstructure based micromechanical model to simulate microstructural level deformation behavior and failure initiation in DP 590 steel

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ABSTRACT

Dual phase (DP) steels having a microstructure consists of a ferrite matrix, in which particles of martensite are dispersed, have received a great deal of attention due to their useful combination of high strength, high work hardening rate and ductility. In the present work, a microstructure based micromechanical model is developed to capture the deformation behavior, plastic strain localization and plastic instability of DP 590 steel. A microstructure based approach by means of representative volume element (RVE) is employed for this purpose. Dislocation based model is implemented to predict the flow behavior of the single phases. Plastic strain localization which arises due to incompatible deformation between the hard martensite and soft ferrite phases is predicted for DP 590 steel. Different failure modes arise from plastic strain localization in DP 590 steel are investigated on the actual microstructure by finite element method.

1. Introduction

Over the last decade, a strong competition between steel and low density metal industries has been observed as a result of increasing requirements of passenger safety, vehicle performance and fuel economy. The response of steel industry to the new challenges is a rapid development of higher strength steels, named advanced high strength steels (AHSSs). These steels are characterized by improved formability and crashworthiness compared to conventional type steel grades. The category of AHSS covers the following generic types: dual phase (DP), transformation induced plasticity (TRIP), complex phase (CP) and martensitic steels (MART). Among AHSS, dual phase (DP) steels are mostly used in automotive industries due to its low yield strength, high work hardening rate and superior formability [1,2]. In general, DP steels are produced by the intercritical heat treatment of low carbon steel, and they consist of composite microstructure of soft ferrite matrix and hard martensite. The flow behavior of dual-phase steels not only depends on the properties of ferrite and martensite but also on the volume fraction and morphology of the martensite islands [3–5], and the partitioning of stress and strain between the two phases during deformation [6–9].

Tremendous efforts have been made by many researchers on exploring various aspects of DP steels. The effect of volume fraction (V_m) of the harder phase (martensite) has been investigated by different authors [4,10,11]. Increasing the volume fraction of the harder phase was found to increase the yield strength and ultimate tensile strength of the aggregate. Bag et al. [4] reported that the increase in strength with V_m only extends up to $V_m \approx 55\%$, after which a reduction in strength is observed. Shen et al. [12] have shown, using a scanning electron microscope equipped with a tensile straining stage, that the distribution of the strains between the ferrite and martensite phases, as well as among the different grains of each phase was observed to be inhomogeneous. They observed that the ferrite phase deformed immediately and with a much more rapid rate than the delayed deformation of the martensite. They had also shown, using scanning electron microscopy that at low V_m only the ferrite matrix deforms, with no measurable strain occurring in the martensite particles. At high V_m, however, they had shown that shearing of the interface between the martensite and ferrite occurs extending the strain into the martensite islands after the ferrite matrix is excessively strained, which is in agreement with Rashid and Cprek [13]. The different stages of strain hardening have been attributed [4,11,13] to the following phases of deformation: (a) both component phases are elastic, (b) the softer phase deforms plastically while the harder phase deforms only elastically and (c) both components deform plastically. Because the flow strength of ferrite is much lower than that of martensite, plastic deformation begins in the soft ferrite. This plastic deformation in the ferrite phase is constrained by the adjacent martensite, leading to localize the deformation in the ferrite. Thus the localized deformation in the ferrite leads to fracture of the DP steel which occurs by decohesion of ferrite–martensite interface or void nucleation and coalescence depending of the morphological difference.

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The strength of martensite depends primarily on its carbon content [5,14]. Whereas, in general the strength of ferrite depends on its composition, and grain size [4,9]. It is now established that the martensite volume fraction is dominant in controlling the tensile properties and increasing the amount of martensite decreases ductility. The previous studies were shown that the morphology of martensite particles also plays an important role in the strength and ductility of the dual phase steels [2,3]. For a constant volume fraction of martensite, a microstructure of finely dispersed martensite has a better combination of strength and ductility. In DP steel the ferrite gets additional strength from the initial dislocation density i.e. strain field, created due to the compatibility stresses and strains when austenite transforms into martensite during cooling [15,16]. This additional strengthening of ferrite adjacent to martensite also causes gradual yielding of DP steels.

Ductile damage/failure can be caused by main three reasons, they are: initial geometrical imperfections [17], void initiation growth and coalescence [18–20] and deformation localization due to microstructure-level inhomogeneity [21–25]. Sun et al. [22,23] have developed a microstructure-based modeling procedure in which the failure mode and ultimate ductility of DP steels are predicted under different loading conditions using the deformation/plastic strain localization theory. Ductile failure is predicted as the natural outcome of the plastic strain localization due to the incompatible deformation between the hard martensite phase and the soft ferrite phase. Similar microstructure-based finite element analysis was used by Choi et al. [24] in predicting the ductility and failure modes of transformation induced plasticity (TRIP) steel. Sun et al. [22] also reported that when the volume fraction of martensite is above 15%, the pre-existing voids in the ferrite matrix does not significantly reduce the overall ductility of the DP steels, and the overall ductility is more influenced by the mechanical property disparity between the two phases.

Strain localization is the earliest stage of fracture process. Strain localization normally leads to localized increase of stress–strain in a particular zone and decrease (i.e. unloading) of stress–strain in the remaining zone. If once strain localization is initiated then, final fracture (i.e. initiation and separation of surfaces) occurs quickly in that localized zone by initiation, growth and coalition of voids or decohesion of ferrite–martensite interface. By knowing the importance of strain localization in fracture process many researchers studied strain localization on different steels; they are DP steels [22,23,26,27], TWIP steels [24], Ferrite–pearlite steel [28], etc. In this work, flow behavior and plastic strain localization of DP 590 steel is investigated.

2. Materials used

DP 590 steel which obtained from USA source in the form of cold rolled strips of 1.00 mm thickness, is used for this investigation. The chemical compositions of DP 590 steel is listed in Table 1.

Tensile specimens of 50 mm gauge length and 12.5 mm gauge width (ASTM E8 [29]) were machined parallel to the rolling direction from the as-received steel sheets. All samples were tested at room temperature using an electro-mechanical tensile testing machine at a crosshead speed of 1 mm min^{-1} which roughly corresponds to a strain rate of 3.33×10^{-4} s^{-1}. For scanning electron microscopy (SEM), the usual 2% nital etched specimens were used. SEM microstructure of DP 590 steel is shown in Fig. 1.

Table 1
Composition of DP 590 steel used, in weight percent.

Steel	C	Si	Mn	Al	P	S	Cu	Cr	N
DP 590	0.09	0.35	0.89	0.04	0.015	0.008	0.025	0.022	0.0054

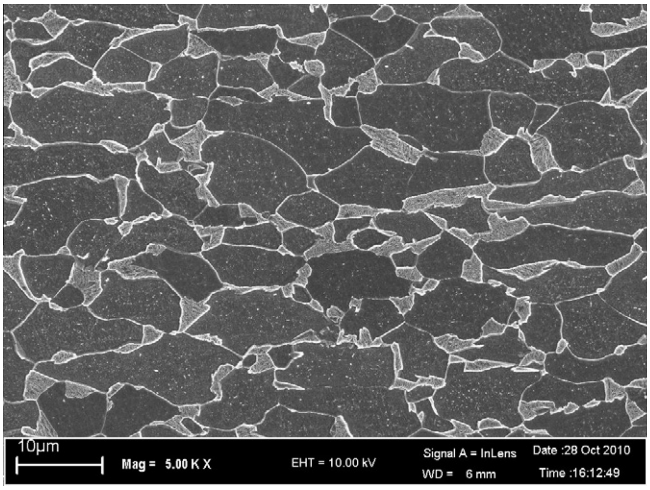

Fig. 1. SEM microstructure of DP 590 steel.

3. Result and discussion

3.1. Constitutive description

In the micromechanical model, the constitutive behavior of the constituent phases will only be required to investigate the aggregate behavior. The interaction of phases (interface boundaries) will be ignored, as it is considerably small, on the order of few atomic sizes, compared to the phases being modeled.

In the elastic–plastic finite element model, von Mises yield criteria, associative flow rule and isotropic hardening rule are assumed for each single phase. To define the isotropic hardening behavior of each individual phase in the calculations, a model based on dislocation theory [27,30,31] is used. The stress–strain relation can be written as

$$\sigma = \sigma_y + \alpha M G \sqrt{b} \sqrt{\frac{1 - \exp(-M K_r \varepsilon)}{K_r L}} \tag{1}$$

where σ is the flow stress at true strain of ε. The explanations of each term are given below and the used values are obtained from a previous study [31]. The second term in Eq. (1) takes care of the dislocation strengthening as well as work softening due to recovery. where α is a constant having a value of 0.33, M is the Taylor factor ($M = 3$), G is the shear modulus ($G = 80$ GPa), b is the Burger's vector ($b = 2.5 \times 10^{-10}$ m), k_r is the recovery rate (for feritte, $k_r = 10^{-5}/d_\alpha$, and for martensite $k_r = 41$). where d_α (m) is the ferrite grain size. L is the dislocation mean free path. For martensite $L = 3.8 \times 10^{-8}$ m [31].

The first term in Eq. (1) is the yield stress which is the summation of friction stress, solid solution strengthening, precipitation strengthening with Nb, Ti and/or V, grain size [32], and it can be described as

$$\begin{aligned} \sigma_y = {} & 70 + 37\mathrm{Mn} + 83\mathrm{Si} + 2918\mathrm{N}_{sol} + 33\mathrm{Ni} - 30\mathrm{Cr} + 680\mathrm{P} \\ & + 38\mathrm{Cu} + 11\mathrm{Mo} + 5000\mathrm{C} + \frac{15.1}{\sqrt{d}} \end{aligned} \tag{2}$$

where the first term (70 MPa) is the stress friction value, d (mm) is the grain Size (mm), alloy content (wt%).

This ferrite–martensite microstructure is obtained by intercritical annealing in the austenite–ferrite region followed by