

Applicability of Micromechanics Model Based on Actual Microstructure for Failure Prediction of DP Steels

K. S. Choi, A. Soulami, W. N. Liu, X. Sun and M. A. Khaleel

Pacific Northwest National Laboratory

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ABSTRACT

In this paper, various micromechanics models based on actual microstructures of DP steels are examined in order to determine the reasonable range of martensite volume fraction where the methodology described in this study can be applied. For this purpose, various micromechanics-based finite element models are first created based on the actual microstructures of DP steels with different martensite volume fractions. These models are, then, used to investigate the influence of ductility of the constituent ferrite and martensite phases and also the influence of voids in the ferrite phase on the overall ductility of DP steels. The computational results indicate that there is a range of martensite volume fraction where the phase inhomogeneity between the ferrite and martensite phases has dominant effect on the overall ductility of DP steels, defeating the influence of the ductility of each phase and the voids in the ferrite phase, and that this phase inhomogeneity dominant region includes the range of martensite volume fraction between 15% and 40%. Therefore, the methodology, adopted in this study, may be applied to DP steels within the phase inhomogeneity dominant region in tailoring the DP steel design for its intended purpose and desired properties.

INTRODUCTION

Dual phase (DP) steels are increasingly being used in various vehicle components. Typical DP steels have a composite microstructure of ferrite and martensite phases that exhibits a favorable combination of strength, high work-hardening rate, ductility and formability over other high strength low alloy (HSLA) steels with similar yield strength. These favorable behaviors of DP steels

are attributable to the combined behaviors of the hard martensite phase with high strength and the soft ferrite matrix with good ductility.

Since the advantages of DP steels were first reported by Rashid [1], a great deal of research has been carried out by many researchers to explore various aspects of DP steels. It is well known that the macroscopic mechanical behavior of DP steels depends on various factors such as the grain size of ferrite and the volume fraction, morphology and carbon content of the martensite phase [2-5]. Fine grain size, high strength and volume fraction of the martensite phase generally increase the tensile strength of DP steels. On the other hand, a high volume fraction of the martensite phase reduces the ductility of DP steels.

Since the macroscopic behaviors of DP steels are attributable to their microstructures, the modeling of DP steels needs to be accomplished on the microstructure level. From this end, micromechanical finite element models have been used to understand the local mechanics and mechanisms governing the macroscopic behavior of heterogeneous materials [6-10]. These models provided some good information on the overall behavior of the heterogeneous materials based on the known properties of the constituents and the detailed interactions among them. Still, most of the studies did not consider the ultimate ductile failure of DP steels, and only a few examined the failure of these complex steels by developing phenomenological failure criteria for prescribed failure mode and intentional critical loading planes. Recently, Sun et al. [11] developed a micromechanics-based modeling procedure for DP steels in which the actual microstructures are used in predicting the failure mode and ductility of DP steels. In

that study, no prescribed failure criterion is used and 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.

Note here that, for the DP steels with lower martensite volume fractions ($V_{f,M}$), the overall deformation/failure behavior of the DP steels can be dominated by the properties (i.e., ductility) of the ferrite phase and vice versa. Therefore, a question may arise about the applicability of the modeling procedure of Sun et al. [11] in terms of the range of the martensite volume fraction in DP steels where their methodology can be adopted without a significant error in the prediction of ultimate ductility. Here, we suppose that there may be some range of martensite volume fraction where the overall behavior of DP steels does not necessarily depend on the properties of the constituent phases. This supposition is presented in Figure 1 which shows that the sources of dominant factors for failure may be different depending on the martensite volume fraction in DP steels. In Figure 1, the range of martensite volume fraction, of interest in this study, is denoted as the phase inhomogeneity dominant region.

The goal of this study is to determine the approximate range of this phase inhomogeneity dominant region. For this purpose, various micromechanics-based finite element models are first generated based on the actual microstructures of DP steels with different martensite volume fractions. These models are, then, used to investigate the influence of ductility of the constituent ferrite and martensite phases and also the influence of voids introduced in the ferrite phase on the overall ductility of DP steels. The applicability of the modeling procedure based on the actual microstructures of DP steels is finally discussed based on the obtained computational results from the various models.

MICROMECHANICS MODELING OF DP STEELS BASED ON ACTUAL MICROSTRUCTURES

Figure 2 shows, on its left column, actual microstructures of several different DP and Transformation Induced Plasticity (TRIP) sheet steels. These pictures were taken by Scanning Electron Microscope (SEM) from the mid-plane along rolling direction of the steels. The microstructures of DP steels in Figures 2(c) [12], 2(e) and 2(f) show very well the ferrite and martensite phases with two clearly different colors. However, the microstructures of TRIP steels in Figures 2(a), 2(b) and 2(d) do not show the difference between the phases as clearly as those of DP steels since TRIP steels have dispersion of two different phases (i.e. bainite and retained austenite) along the grain boundaries of the ferrite matrix. After numerical image processing of the actual microstructures shown in Figure 2, the resulted corresponding finite element discretization are also shown on the right column in the

figure, which are used as the Representative Volume Elements (RVEs) of DP steels with different martensite volume fractions in this study. Note here that two different RVEs with different martensite volume fractions (i.e., $V_{f,M} = 25\%, 31\%$) were obtained based on the same actual microstructure shown in Figure 2(d) by adjusting a portion of bainite and/or retained austenite phases to become the martensite phase and only the RVE with martensite volume fraction of 25% is shown here due to the similarity of the two RVEs. As a result, in this study, seven different RVEs were created in total with different martensite volume fractions. In all of the RVEs, only the ferrite and martensite phases are considered to be present and perfect bonding is assumed between the two phases. In some RVEs, the grain boundaries are explicitly modeled with finer meshes for later investigations of the failure initiation points. The martensite volume fractions ($V_{f,M}$) in the RVEs are ranged between 7% and 44%, as marked in the figure caption. This is believed to a reasonable range of the martensite volume fraction in general DP steels. In addition, as for the representativeness of the RVEs based on the actual microstructures, it should be noted here that different RVEs with similar martensite volume fractions and similar statistics of martensite grain morphologies obtained from the actual microstructures seem to predict similar overall stress versus strain behaviors [11].

In this study, we focus on the in-plane deformation behavior/failure of DP sheet steels. Since the sheet specimen is relatively thin as compared to its in-plane dimensions and that it is also subjected to in-plane loading during uniaxial tensile tests, the sheet specimen may be generally considered to be under plane stress state. As the commercial finite element code ABAQUS [13] was used in this study, two-dimensional plane stress CPS3 elements are adopted in the analyses to simulate the in-plane deformation behaviors of DP sheet steels under tensile loading conditions.

The uniaxial tensile loading along the rolling direction (x direction of the RVEs) is examined in this study. In order to simulate this loading condition, all the nodes along the right edge are given the same displacements in the x direction while they can freely move in the y direction during the tensile loading. Here, all the nodes along the left edge are constrained not to move in the x direction, but are allowed to freely move in the y direction. Since the RVE is assumed to be the representative in-plane microstructure of DP steels, the macroscopic engineering stress is obtained by dividing the reaction force of the RVE in the x direction with the initial area, i.e., the initial thickness for the plane stress model. The engineering strain in the x direction is obtained by dividing the displacements of the right edge with the initial length of this model.

For finite element analysis, both the ferrite and martensite phases are assumed to have elastic-plastic isotropic hardening behaviors under loading. The plastic flow stresses for the ferrite and martensite phases are assumed to satisfy the following laws, respectively.

$$\sigma_0 = \sigma_{y,F} + K_F \varepsilon_{ep}^{n_F} \quad (1a)$$

$$\sigma_0 = \sigma_{y,M} + K_M \varepsilon_{ep} \quad (1b)$$

Here, $\sigma_{y,F}$ and $\sigma_{y,M}$ represent the initial yield strengths and K_F and K_M represent the hardening coefficients for the ferrite and martensite phases, respectively. n_F represents the hardening exponent for the ferrite phase. Note here that the martensite phase is assumed to have linear hardening behavior.

The benchmark mechanical properties of the ferrite and martensite phases in the RVEs of DP steels are determined from the in-situ High-Energy X-Ray Diffraction (HEXRD) test together with the uniaxial tensile tests of a DP 980 steel [11]: $\sigma_{y,F} = 425$ MPa, $K_F = 940$ MPa, $n_F = 0.2$, $\sigma_{y,M} = 1180$ MPa and $K_M = 1740$ MPa. Figure 3 shows the input stress-strain curves for the ferrite and martensite phases in this study. In Figure 3, the macroscopic response of the DP 980 RVE, shown in Figure 2(e), based on these input stress-strain curves and the experimental result are also plotted for the purpose of comparison. As shown in Figure 3, predicted macroscopic response of the RVE are in good agreement with experimental measurements. It is also noted here that, with the determined mechanical properties of the two phases above, the predicted failure modes of the RVE under different stress states are in excellent agreement with the local failure modes observed in the uniaxial tensile tests of the DP 980 sheet specimen [11].

The mechanical properties of the constituent phases in DP steels depend on the chemistry and thermo-mechanical process in steel production and, therefore, can be quite different even for the same grade DP steels, not to mention the different grade DP steels (with different martensite volume fractions). In this study, however, we adopted only one set of mechanical properties for the ferrite and martensite phases, shown in Figure 3, since the effects of martensite volume fraction on the dominant source for the failure (i.e. ductility) of DP steels are of interest. The effects of strength of the martensite phase on the failure of DP steels are reported in detail in Choi et al. [14]. Again, in this study, no prescribed failure criterion is used for the two phases and 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.

INFLUENCE OF CONSTITUENT PHASE PROPERTIES ON OVERALL DUCTILITY OF DP STEELS

INFLUENCE OF DUCTILITY OF CONSTITUENT PHASES – In this section, we investigate the influence of ductility of the ferrite and martensite phases on the overall ductility of DP steels using the different RVEs shown in Figure 2. For this purpose, we varied the strain range of the input stress-strain data (i.e., the maximum strain value of the input data) for the two phases, which follow the input stress-strain curves shown in Figure 3.

Figure 4 shows the engineering stress-strain curves of four different RVEs under uniaxial tensile loading as function of input strain range of ferrite with fixed input strain range of martensite. Here, the input strain ranges of the ferrite and martensite phases are varied between 30% and 150% and fixed as 50%, respectively, in order to examine the influence of ductility of ferrite phase. For the RVEs with relatively small volume fraction of martensite, overall ductility of the RVE generally increases as the input strain range of ferrite phase increases as shown in Figures 4(a) and 4(b). For the RVEs with relatively large volume fraction of martensite, however, the effects of input strain range of ferrite phase on the overall ductility seem to be negligible since most of the stress-strain curves are nearly collapsed as one curve except for the case of input strain range of 30% for ferrite phase as shown in Figures 4(c) and 4(d). Here, the tested input strain range of 30% for ferrite phase is believed to be so low as to have dominant effect on the overall ductility of the RVEs of entire range of martensite volume fraction. Therefore, we focus here only on the cases of input strain range between 50% and 150%. Note that, in Figure 4, the results are presented only for four different RVEs for brevity of paper and that the results for the other RVEs show very similar trends mentioned above. From the stress-strain curves as function of input strain range of ferrite phase in Figure 4, it is observed that the overall ductility of DP steels may be dominated by the ductility of ferrite phase for DP steels with the martensite volume fraction less than 15% whereas it may be dominated by the phase inhomogeneity between the two phases for DP steels with the martensite volume fraction more than 15%, regardless of the ductility of ferrite phase.

Figure 5 shows the engineering stress-strain curves of the different RVEs under uniaxial tensile loading as function of input strain range of martensite with fixed input strain range of ferrite. Here, the input strain ranges of the ferrite and martensite phases are fixed as 100% and varied between 10% and 50%, respectively, in order to examine the influence of ductility of martensite phase. Since the martensite is known to be brittle, relatively low input strain range between 10% and 50% were selected here for the martensite phase. Similarly, based on the observation on the stress-strain curves as function of