Uniaxial tension simulation using real microstructure-based representative volume elements model of dual phase steel plate

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Abstract

Dual-phase steels have become a favored material for car bodies. In this study, the deformation behavior of dual-phase steels under uniaxial tension is investigated by means of 2D Representative Volume Elements (RVE) model. The real metallographic graphs including particle geometry, distribution and morphology are considered in this RVE model. Stress and strain distributions between martensite and ferrite are analyzed. The results show that martensite undertakes most stress without significant strain while ferrite shares the most strain. The tensile failure is the result of the deforming inhomogeneity between martensite phase and ferrite phase, which is the key factor triggering the plastic strain localization on specimen section during the tensile test.

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Keywords: Microstructure based modeling; Representative volume element; Dual phase steel; Plastic strain localization

1. Introduction

Dual-phase (DP) steels have become a favored material for car bodies due to the attractive combination between strength and formability. These properties are achieved by embedding hard and brittle martensite phase into the soft and ductile ferrite matrix.

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The macroscopic mechanical properties of DP steels depend on various factors such as martensite and ferrite phase mechanical properties, volume fraction and morphology of martensite, as well as grain size (Kim et al, 1986; Erdogan, 2002; Erdogan et al, 2002; S. Sun et al, 2002). Since the macroscopic mechanical behavior of DP steels strongly depend on their microstructures, micromechanics based models have been used to understand the local deformation mechanics, strain distribution and strain localization of DP steels (Uthaisangsuk et al, 2008,2009; X. Sun et al, 2009; Choi et al, 2009).

It is well known that loss of uniform deformation in simple tension of plastic materials is related to the reaching of the peak nominal stress. The strain localization leads to plastic instability and fracture. Plastic instability is traditionally considered modelling in two ways: (1) the classical Marciniak-Kuczynski (‘M-K’) model (Marciniak et al,1967) by introducing initial geometrical imperfections, and (2) damage and void-growth theories: the popular Gurson-Tvergaard-Needleman (GTN) model (Gurson,1975; Tvergaard,1982; Tvergaard et al, 1984). Source of initial imperfection triggering the plastic instability is demonstrated as the material microstructure-level inhomogeneity (Chatzigeorgiou et al, 2005) between the hard martensite phase and the soft ferrite phase in DP steels.

In this paper, a real microstructure-based RVE model of DP steel is established. For comparison, a random martensite distribution RVE model is studied first. Microstructure based RVE models are established afterwards to study the deformation behavior of DP steels in tensile test with three different locations. Stress and strain distributions between martensite phase and ferrite phase are analyzed.

2. RVE modelling

2.1. Materials

DP steels are composed of martensite and ferrite phases, and these two microstructures exhibit different mechanical properties. Fig. 1 shows the true stress–strain curves of each phase from literature (S. K. Pual, 2012). Table 1 is the material properties of DP780, which are acquired by standard uniaxial tensile tests according to GB/T 228-2010 (ASTM E8).

![Fig. 1. True stress-strain curves of martensite and ferrite in DP steels.](image-url)

<table>
<thead>
<tr>
<th>Material</th>
<th>YS $\sigma_y$ (MPa)</th>
<th>UTS $\sigma_t$ (MPa)</th>
<th>TE (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>DP780</td>
<td>461</td>
<td>802</td>
<td>27.1</td>
</tr>
</tbody>
</table>
2.2. Geometric Models

RVE geometric models are created and imported into ABAQUS/Standard, and different material properties of martensite and ferrite are assigned to geometric parts.

(a) Random distribution RVE geometric model

The volume fraction of martensite in DP780 is 37% by processing the photomicrographs. A RVE geometric model with random distribution of martensite is created and displayed in Fig. 2. The brown part is ferrite and green is martensite. There are 140 green squares distributed in the 20x20 matrix using random function, which indicates the martensite volume fraction is 35%. 4-node square elements are used in the modelling of random distribution RVE model to represent the homogeneous materials with different phase. Element type of both phases is S4R.

(b) Microstructure-based RVE geometric model

Metallographic structure of DP780 with 500× is obtained using optical microscope. Martensite phase and ferrite phase can be distinguished by grayscale in photomicrograph (Fig. 3a): the white part is ferrite while the gray part is martensite. Typical region of the photomicrograph with 37% martensite is chosen to model and analyse deformation behavior in simulation. The phase boundary of martensite and ferrite is generated using UniGraphics NX with splines, which is shown in Fig. 3b. Martensite and ferrite phases are marked respectively in the figure. Since the martensite phase of DP780 is more continuous than the ferrite phase, ferrite phase is divided into islands and phase boundary of ferrite is traced. Then the microstructure-based RVE geometric model is created.

2.3. Boundary conditions

Three locations of different stress and strain states are selected in tensile test specimen (Fig. 4a). In Fig. 4b, Location A and B are regarded as plane stress state. These locations are both in X-Y plane, while in Y-direction,
Location A has a free deformation on the top edge, but Location B is restrained with both edges. Location C is in the X-Z plane with plane strain state, and the boundary condition of Location C in Z-direction is unrestricted. Among all the Locations, the X-direction is tensile loading direction, and in this direction the constraints of edges are applied according to the stress and strain acquired in tensile test simulation.

Boundary conditions are displacement control in simulation. Shell element is selected which takes into account both the computational efficiency and accuracy. Then the models are meshed and submitted for analysis.

![Fig. 4. Microelements in three different locations: (a) uniaxial tensile test; (b) Location A, B and C.](image)

### 3. Results and discussion

Random distribution RVE model and microstructure-based RVE model are analysed according to the stress strain states of Location A, B and C. The engineering stress-strain behaviour and strain distributions are discussed.

#### 3.1. Engineering stress-strain curve

By controlling the displacement of the edge in the models, the total elongation of the whole RVE model $\Delta l$ is calculated. Total reaction force at the edge nodes $F$ is accumulated. The engineering stress-strain curve is obtained by

$$
\varepsilon = \frac{\Delta l}{l_0}
\quad \sigma = \frac{F}{S},
$$

where $\varepsilon$ is engineering strain, $\sigma$ is engineering stress, $l_0$ is the original length and $S$ is the model width which represents the cross-sectional area in 2D models.

![Fig. 5. Engineering stress-strain curves of simulation and test: (a) random distribution model; (b) Microstructure-based model.](image)
Simulation data of random distribution model is shown in Fig. 5a. It coincides well with the experimental data in elastic deformation. But diversity appears clearly in plastic deformation, and the gap increases as strain increases. Fig. 5b is stress-strain curves of microstructure-based model, the simulation and experimental data match well both in the elastic deformation and plastic deformation.

During elastic deformation, according to the stress and strain relationship \( \sigma = E \varepsilon \), stress-strain curve is decided by the elastic modulus, while the elastic moduli of martensite and ferrite are the same. In plastic deformation, simulation results depend on the geometry of martensite phase and the distribution of martensite in ferrite, since mechanical behaviors of martensite and ferrite are different, and deformation compatibility also plays a part. Not only volume fraction but also phase morphology should be taken into account. Comparing to the random distribution model, simulation accuracy is greatly improved by adding phase geometry and morphology information.

3.2. Strain and failure analysis

Equivalent plastic strain of Location A, B and C at the same loading time in tensile tests is compared. Fig. 6 presents the equivalent plastic strain contours of Location A, B and C. The tendency of strain distribution in Location A and C is similar. Both of them show shear bands appearance. The strain distribution in Location B is more centralize in the direction perpendicular to the stretching direction. Maximum strain in the white ellipse area at the bottom of Location B is lower than the maximum strain in the white rectangular area, so it is considered that the fracture perpendicular to the stretching direction in Location B is dominant.
In traditional plastic theory, local strain concentration position is most probably where the voids form and grow up till crack. Location A and Location C fails in the form of shear band, but Location B is splitting failure. Since failure mode of Location C is similar to Location A, and the fracture surface is not easy to observe, uniaxial tensile fracture specimen of Location A and B is shown Fig. 7. They are in good agreement with the simulation.

Specimens are also observed in SEM (Scanning Electron Microscope). Fracture morphology is shown in Fig. 8. Location A has larger and deeper dimples in tensile direction in the fracture morphology than Location B, which means that strain of Location A is greater. The SEM also indicates that Location A is shear band failure, and Location B is splitting failure.

4. Conclusions

(1) In RVE modelling, the microstructure and phase morphology should be taken into account. The real microstructure-based RVE model is more accurate than random distribution model.

(2) The three different stress and strain states in uniaxial tension will affect the boundary conditions of RVE model, which will lead to different stress distributions and strain concentrations.

(3) Two micro-failure modes are investigated in DP780. Both shear failure in plane stress conditions and splitting failure in plane stress conditions are observed.

Acknowledgments

This work is supported by the National Natural Science Foundation of China under Grant No. 51075267 and International cooperation program in science and technology of MOST China under Grant No. 2010DFA72760. The authors are grateful to other colleagues for their help in experiments.

References