20th European Conference on Fracture (ECF20)

Influence of volume fraction and distribution of martensite phase on the strain localization in dual phase steels

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Abstract

The present work investigates by finite element (FE) analysis the effects of volume fraction and distribution of martensite phase on the strain localization in three commercial dual-phase (DP) steels. Strain localization is considered here as a precursor to fracture. The microstructures of the investigated steels were explicitly represented in the FE model using the representative volume element (RVE) approach. The properties of the ferrite and the martensite were determined from tensile test data for the investigated steels using an inverse identification procedure. The strain field in each phase was determined and related to the distribution of the martensite in the soft ferrite phase. Strain localization in the hard martensite phase was discussed with respect to fracture initiation and propagation in the investigated DP steels. The numerical results are coherent with microstructural observations of fracture initiation in DP steels.

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Selection and peer-review under responsibility of the Norwegian University of Science and Technology (NTNU), Department of Structural Engineering

Keywords: Strain Localization; Dual phase steel; Martensite; Ferrite; Representative volume element; Finite element model; Fracture initiation

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1. Introduction

In dual phase materials, fracture initiates by microcracking of particles or interfaces and proceeds by crack or void extension into the neighboring microstructures. The microcracks in DP steel can be initiated by martensite cracking, separation of adjacent martensite regions or by decohesion at the ferrite-martensite interface (Avramovic-Cingara et al, 2009; Erdogan and Tekeli, 2002). Different propagation modes are also observed in DP steels (Wang and Wei, 2013; Kim and Thomas, 1981). The nucleated voids may grow and coalesce along the ferrite-martensite interfaces or across the martensite. These different mechanisms of fracture are related to the chemical composition, the volume fraction and distribution of the phases, and the grain characteristics of the ferrite and martensite phases. These microstructural features affect the partitioning of stress and strain between the two phases and influence the activated modes of fracture. In order to predict fracture of particular DP steels, one needs to have an understanding of the influence of the constituent phases on the distribution of stress and strain in each phase during deformation.

The aim of the present work is to set up a numerical model to study the effects of the microstructure on the stress and strain distribution, considering strain localization as a precursor to fracture. As a first step, a representative volume element of the DP steel microstructure was discretized with finite elements to incorporate explicitly the influences of the volume fraction and distribution of martensite on the partitioning of stress and strain between the two phases. The strain localization in the ferrite and martensite phases was studied for three commercial DP steels and linked to the distribution of the martensite phase. The RVEs of these steels were generated by a numerical process accounting for the volume fraction of martensite, the average size of the martensite islands and the grain size of the ferrite. The mechanical properties of the ferrite and martensite were determined by an inverse identification procedure using the tensile test data for the investigated steels.

2. Experiments

The study includes three commercial DP steels with strength levels from 500 MPa to 1000 MPa. This section briefly describes the microstructure characteristics and tensile properties of these steels. More detailed information can be found in Bergström et al (2010).

The investigated DP steel grades were continuously cast to slabs, reheated in the slab reheating furnace, and hot rolled according to normal production routines at SSAB. The final properties of each grade were achieved by subsequent cold rolling and annealing processes in a continuous annealing line using the parameters presented in Table 1. The nominal chemical compositions of the investigated steels are also presented in this table.

<table>
<thead>
<tr>
<th>Grade</th>
<th>C [%]</th>
<th>Mn [%]</th>
<th>Si [%]</th>
<th>Nb [%]</th>
<th>T (soaking) [ºC]</th>
<th>T (tempering) [ºC]</th>
<th>Strain (rolling)</th>
</tr>
</thead>
<tbody>
<tr>
<td>DP500</td>
<td>0.08</td>
<td>0.65</td>
<td>0.30</td>
<td>—</td>
<td>760</td>
<td>300</td>
<td>0.6</td>
</tr>
<tr>
<td>DP800</td>
<td>0.13</td>
<td>1.50</td>
<td>0.20</td>
<td>0.015</td>
<td>760</td>
<td>300</td>
<td>&lt;0.2</td>
</tr>
<tr>
<td>DP1000</td>
<td>0.15</td>
<td>1.50</td>
<td>0.5</td>
<td>0.016</td>
<td>780</td>
<td>210</td>
<td>&lt;0.2</td>
</tr>
</tbody>
</table>

The microstructures of the studied steels were examined by scanning electron microscopy (SEM), see Fig. 1. The martensite phase appears in this figure as light areas and the ferrite matrix as dark gray areas. The microstructure of DP500 is characterized by coarse martensite islands and a coarse-grained ferrite phase. A more refined microstructure is observed for DP800 and DP1000, where the martensite phase is more dispersed in the ferrite phase. The increased volume fraction of the martensite decreases the distance between the martensite islands in DP1000 compared to DP800 and DP500. The volume fraction of martensite $f_m$ is given in Fig. 1 as the average of two
surface fractions measured using an image processing technique. The scatter in martensite fraction is about ±2% for each sample.

Tensile testing was performed at room temperature and a constant strain rate of $2.5 \times 10^{-3}$ [s$^{-1}$] was applied for all samples. The engineering stress-strain curves obtained by tensile testing are illustrated in Fig. 2. As expected, the tensile strength increased with increasing fraction of the hard martensite phase. The soft ferrite phase increased the ductility of the DP steel, where DP500 has higher tensile elongation compared to DP1000. The difference in the yield stress observed for the three steels was related to the ferrite grain size and the martensite distribution (Bergström et al, 2010; Ramazani et al, 2012), where finer grains of the ferrite phase (see Fig. 1) increase the yield stress of the DP steel.

![Fig. 1. SEM images of the investigated steel grades with the fraction of the martensite ($f_m$) and the grain size of the ferrite ($d_f$).](image1)

![Fig. 2. Engineering stress-strain curves obtained by tensile testing of the investigated steel grades.](image2)

3. Finite element model

The RVEs for the different steels were generated using a two-step numerical process in which the average size of the ferrite grain and the martensite islands were firstly used to generate a periodic, polycrystalline RVE. The volume fractions of the phases were then used to divide the polycrystal into two sets of elements representing the martensite
phase and the ferrite phase, respectively. The generated RVEs for the different steels are presented in Fig. 3. A refined mesh was used in order to describe the stress and strain gradients inside the phases with good accuracy. The total number of elements in the mesh was 62500. The interactions between the phases were accounted for by assuming displacement continuity of the finite elements at the interface between the phases. The boundary conditions used by Saai et al (2013) were adopted here to model the uniaxial tensile loading. Periodic boundary conditions were applied to the nodes located on the faces of the RVE in order to ensure periodicity in displacements and thus to minimize constraint effects.

![Representative volume elements of the investigated DP steel grades.](image-url)

The responses of the martensite phase and the ferrite phase were computed by an elasto-plastic model with the von Mises yield function, the associated flow rule and an isotropic hardening law. The von Mises equivalent stress in each phase is given by:

$$\sigma_{eq} = \sigma_y + \sum_{i=1}^{N} Q_i \left[1 - \exp \left(-\frac{\theta_i}{Q_i} e^{P}_{eq}\right)\right],$$  

where the first term on the right-hand side, $\sigma_y$, is the yield stress of the phase and the second term is the isotropic hardening defined by a two-term Voce rule ($N = 2$). The hardening parameters $Q_i$ and $\theta_i$ are respectively the initial hardening rate and the saturated value of the hardening term $i$ while $e^{P}_{eq}$ is the equivalent plastic strain. The values of these parameters are given in Table 2. The DP steel is supposed to yield at the yield stress of the soft ferrite phase which depends on the grain size of the ferrite and the martensite distribution (Bergström et al, 2010; Ramazani et al, 2012). This explains the different values of yield stress of the ferrite phase presented in Table 2. The yield stress of the martensite and the hardening parameters of the ferrite and the martensite are considered here independent of the martensite content. These parameters were determined by an inverse identification procedure using the true stress-strain curves of the investigated steels. The RVEs presented in Fig. 3 and the calibrated material models for the martensite and ferrite phases were used in implicit finite element simulations (Abaqus, 2012) of the tension tests. Fig. 4 shows true tensile stress-strain curves obtained by the numerical simulations and compares them to the experimental curves. As can be observed, the models predict the tensile stress-strain curves of the different grades with good accuracy.

<table>
<thead>
<tr>
<th>Grade</th>
<th>$\sigma^f_y$</th>
<th>$\theta^f_1$</th>
<th>$Q^f_1$</th>
<th>$Q^f_2$</th>
<th>$\sigma^m_y$</th>
<th>$\theta^m_1$</th>
<th>$Q^m_1$</th>
<th>$Q^m_2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>DP500</td>
<td>276</td>
<td>4300</td>
<td>60</td>
<td>2000</td>
<td>250</td>
<td>1100</td>
<td>25000</td>
<td>450</td>
</tr>
<tr>
<td>DP800</td>
<td>440</td>
<td>650</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>DP1000</td>
<td>650</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
4. Results and Discussion

The stress and plastic strain fields in each phase were computed for the different steels at nominal strains corresponding to the ultimate tensile stress (i.e., nominal strain of 0.2, 0.13 and 0.08 for DP500, DP800 and DP1000 respectively, see Fig. 2). The deformed phases with contours of equivalent plastic strain and von Mises equivalent stress are presented in Fig. 5. The stress in the ferrite phase was found to be affected by the martensite content where the increased fraction of the martensite reduces the areas of elements with maximum stress. In DP500, the gradient of stress was observed in narrow areas close to the interface with the martensite island while homogenous distribution of the stress was found inside the phase. The strains in the ferrite and the martensite were also affected by the volume fraction and distribution of the martensite. In the martensite phase, high strains were observed in the elements at the ferrite-martensite interfaces. The localized deformation at the ferrite-martensite interface suggests that fracture might be initiated at the interface, which is in coherence with the microstructural observations on the initiation of microcracks in DP steels (Avramovic-Cingara et al, 2009). However, the strain localization at the ferrite-martensite interface cannot explain whether the microcracks would nucleate by martensite cracking or by decohesion at the ferrite-martensite interface. The dispersed martensite in DP800 and DP1000 increases the localized strains in the elements at the ferrite-martensite interface. This is expected to increase the nucleation of microcracks and reduce the distance between them, thus facilitating fracture propagation and reducing the deformability of these materials (Wang and Wei, 2013).

High strain gradients were observed in DP500 where the core of the martensite islands was undeformed and the maximum plastic strain was associated to the elements on the ferrite-martensite interface. This suggests that fracture will propagate in this material along the ferrite-martensite interfaces which is coherent with the fracture propagation in DP steels with coarse martensite islands (Wang and Wei, 2013; Kim and Thomas, 1981). The strain gradients in the martensite phase were less pronounced in DP800 and DP1000 where the core of the martensite islands was more strained. This increases the possibility of fracture propagation within the martensite phase (Wang and Wei, 2013).

![Fig. 4. True stress-strain curves computed by the finite element model compared to the experimental curves obtained by tensile tests.](image)

5. Conclusion

The influence of volume fraction and distribution of martensite on strain localization in DP steels was investigated by FE models using the RVE approach. The volume fraction of the martensite and its distribution in the
ferrite phase were explicitly represented in the FE model. The properties of each phase were determined by an inverse identification procedure using tensile test data for the investigated steels. Stresses and strains were computed for each phase and presented at a nominal strain corresponding to the ultimate tensile stress. The localization of strains in the martensite and ferrite phases depends on the distribution of the martensite in the soft ferrite phase. The strains in the martensite phase are localized at the ferrite-martensite interface, indicating initiation of fracture in this area, in accordance with microstructural observations of the void nucleation in DP steel. More dispersed martensite with refined martensite islands increases strain localization and decreases the strain gradient in the martensite. This is expected to increase the nucleation of microcracks formed during plastic deformation of the material and thus facilitate fracture propagation.

Fig. 5. Deformed phases with contours of equivalent plastic strain (a, b) and deformed ferrite phase with contours of the von Mises equivalent stress (c).

References