Numerical Simulations of Formability of Multiphase Steels

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Abstract. In this paper we investigate the formability of multiphase steels. A new model based on crystal plasticity has been developed to investigate large strain phenomena in multiphase steels. The approach is based on the concept of a unit cell. The unit cell is defined as a globally small region of the sheet that contains all the essential micro-structural and textural features that characterize the sheet. Orientations within the measured texture data are randomly assigned in the mesh/unit cell. In other words, each element of the mesh represents an orientation from the measured texture and the constitutive response at a material point is given by the single crystal constitutive model.

This model is employed to construct forming limit diagrams for multiphase steels.

INTRODUCTION

Over the last decade, lightening of the automobile body has become a serious issue since the lightening of the weight directly contributes to the improvement of the fuel consumption of cars. The weight of automobiles can be reduced by using high-strength steels as long as they have the essential ductility required in metal forming operations [1]. It has been well established that low-carbon multiphase steels developed in the past decades offer promising mechanical properties such as high work hardening rates and good ductility. Since these steels have microstructures consisting of two or more ductile phases it is essential to understand how the properties of the individual grains of the different phases combine to form the macroscopic properties of the multiphase steel.

Mainly analytical approaches have been employed in the past to model the dual phase (DP) steel material behaviour. However these models were based on the assumption of uniform deformation between the two phases; thus the local strain gradients were neglected. Recently, an axisymmetric unit cell model based on a regular array of second-phase particles arranged on a BCC lattice was employed to study the deformation mechanism of ferrite-pearlite structural steels [2]. The proposed BCC cell model was able to accurately simulate the tensile behaviour of the ferrite-pearlite steels. Ferrite-pearlite flow curves were simulated using FE analyses with regression equations for flow curves of each ferrite and pearlite phases [3]. However, the predicted flow curves were lower than the experimentally measured ones mainly due to the simplicity of pearlite morphology for FE analysis. Different idealizations based on the micromechanical modeling of cells for dual phase steels were explored and compared [4]. Their research concluded that the stacked-hexagonal-array (SHA) axisymmetric cell model was able to capture the expected material behaviour in terms of the trend of the stress-strain curves.

In metal-forming processes involving thin sheets, the onset of localized necking is an important failure mode that limits formability. The concept of a forming limit diagram (FLD), first introduced by Keeler [5] from his investigation of plastic instability and fracture in sheets stretched over steel punches, has proved to be extremely useful for representing conditions for the onset of sheet necking. It is now a standard tool for characterizing materials in terms of their formability and stretchability. Most theoretical and numerical studies of FLDs have been based on the so-called M-K analysis developed by Marciniak and Kuczynski [6]. In the M-K analysis, thickness imperfections are introduced to simulate pre-existing defects in the sheet material. Necking was considered to occur when the ratio of the thickness in the groove to the nominal thickness was below a critical value. This analysis...
combined with crystal plasticity theory has been employed to predict FLDs for sheet metals [7, 8].

In this paper, a new model based on crystal plasticity has been developed to investigate the formability of multiphase steels. In this model, each element of the finite element mesh represents a single crystal, and the constitutive response at a material point is given by the single crystal constitutive model. The new model is employed to construct the FLD of a dual phase steel alloy. Henceforth, this model will be referred to as FE/grain model.

**CONSTITUTIVE MODEL**

A rigorous framework for the kinematics of the finite plastic deformation of a crystal has been firmly established for some time. This basic formulation has been incorporated into a rate-dependent description of crystal plasticity constitutive relations [9, 10]. Within a BCC crystal, plastic deformation occurs by crystallographic slip on 24 distinct slip systems. In the rate-sensitive crystal plasticity model employed, the elastic constitutive equation for each crystal is specified by:

\[
\dot{\sigma} = \mathbf{L} \cdot \mathbf{D} - \sigma^\gamma - \sigma^\tau \mathbf{D}
\]

where \(\sigma\) is the Jaumann rate of Cauchy stress, \(\mathbf{D}\) represents the strain-rate tensor and \(\mathbf{L}\) is the tensor of elastic moduli. The term \(\sigma^\gamma\) is a viscoplastic type stress rate that is determined by the slip rates on the 24 slip systems of a BCC crystal. The slip rates are taken to be governed by the power law expression

\[
\dot{\gamma}_{(\alpha)} = \gamma_{(0)} \text{sgn} \frac{\tau_{(\alpha)}}{g_{(\alpha)}} m
\]

where \(\gamma_{(0)}\) is a reference shear rate taken to be the same for all the slip systems, \(\tau_{(\alpha)}\) is the resolved shear stress on slip system \(\alpha\) (\(\alpha\) ranging from 1 to 24), \(g_{(\alpha)}\) is its hardness and \(m\) is the strain-rate sensitivity index.

The single slip hardening law employed in this paper takes the following power-law form:

\[
h_{(\alpha)} = h_0 \left( \frac{h_0 \gamma_{(\alpha)}}{\tau_{(\alpha)}} + 1 \right)^{n-1}
\]

where \(h_0\) is the system’s initial hardening rate, \(n\) is the hardening exponent and \(\gamma_{(\alpha)}\) is the accumulated slip.

**PROBLEM FORMULATION**

The unit cell is defined as a globally small region of the sheet that contains all the essential micro-structural and textural features that characterize the sheet [11, 12]. The sheet itself is subject to plane stress conditions (i.e. \(\sigma_{33} = 0\)). Orientations within the measured texture data are randomly assigned in the mesh/unit cell. In other words, each element of the mesh represents an orientation from the measured texture. Furthermore different material properties for different phases are mapped onto each individual grain within the polycrystal aggregate. The loading imposed on the edges of the unit cell is assumed to be constant (Figure 1), such that

\[
\frac{\dot{\epsilon}_{22}}{\dot{\epsilon}_{11}} = \rho
\]

where \(\dot{\epsilon}_{22}\) and \(\dot{\epsilon}_{11}\) are the (principal) logarithmic strain rates. Thus, uniaxial tension along direction 1,

**FIGURE 1.** Schematic representation of a unit cell.
in-plane plane strain in direction 1 and balanced biaxial tension correspond to \( \rho = -0.5 \), \( \rho = 0 \) and \( \rho = 1 \) respectively.

**RESULTS AND DISCUSSION**

The initial texture (represented by 400 grains) employed in the simulations is presented in Figure 2. It should be mentioned that even though the initial texture is represented by 400 grains, 3600 elements are used in the simulations. Thus each orientation within the initial texture is represented 9 times in the FE mesh. This approach was employed since increasing the number of representations per grain within the FE mesh decreases the effect of the spatial orientation distribution of the measured texture.

**FIGURE 2.** Initial texture represented in terms of \{111\} pole figure.

The true stress–strain curves for the two different phases are presented in Figure 3. Note that these are two phases chosen randomly. Furthermore, in the simulations, the volume fractions of phase 1 and phase 2 are taken to be 60% and 40% respectively. Note that 60% of the grains in the initial texture assigned to phase 1 and 40% of the grains assigned to phase 2 were chosen randomly. The material properties employed to obtain the stress-strain curves in Figure 3 are presented in Table 1. The slip system reference plastic shearing rate \( \dot{\gamma}_0 \) and the slip rate-sensitivity parameter \( m \) are taken as \( \dot{\gamma}_0 = 0.001 \text{s}^{-1} \), and \( m = 0.05 \), respectively with the crystal elastic constants taken as \( C_{11} = 206 \text{ GPa}, C_{12} = 118 \text{ GPa} \) and \( C_{44} = 54 \text{ GPa} \) for both phases.

The predicted FLD for the dual phase steel is presented in Figure 4. It should be mentioned that for this specific study, the criteria of maximum stress has been employed to determine the limit strains to construct the FLD. Thus, the response of the unit cell under biaxial tension is calculated using the finite element method and the corresponding in-plane principal logarithmic strains of the unit cell (along directions 1 and 2 in Figure 1) at the strain level where the true stress (in the major strain direction) reaches a maximum are used a point on the FLD. The entire FLD of a sheet is determined by repeating the procedure for different deformation paths as prescribed by the strain rate ratio \( \rho \). Note that localized deformation is the natural outcome of the FE/grain model and an initial thickness imperfection required by the M-K analysis is not necessary for the FE/grain model [11].

**TABLE 1.** Material parameters used in the simulations

<table>
<thead>
<tr>
<th>Phase</th>
<th>( \tau_0 ) (MPa)</th>
<th>( h_0 / \tau_0 )</th>
<th>( n )</th>
<th>( q )</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>29.7</td>
<td>34.23</td>
<td>0.18</td>
<td>1</td>
</tr>
<tr>
<td>2</td>
<td>30.4</td>
<td>51.28</td>
<td>0.21</td>
<td>1</td>
</tr>
</tbody>
</table>

**FIGURE 3.** True stress–strain curves for the two phases

The results presented in this paper were obtained by random material properties for the two phases since the main goal of this research was to demonstrate the capability of the FE/grain model to predict the limit strains for multiphase materials without an initial imperfection. It should also be mentioned that there are two major difficulties with the proposed model. The first one is the criteria used to determine the limit strains to construct the FLD. The onset of diffuse necking was employed as the criteria to determine limit strains in this research mainly because of the length of the simulations and also because of the fact that a unique criterion for the onset of localized necking is still open to discussions.
The second difficulty is the dependency of the predictions with the FE/grain model on the spatial orientation distribution of a measured texture. Randomization techniques such as the one employed in this paper and electron backscattering diffraction (EBSD) technique could be used to overcome this problem.

Finally, it should be emphasized that the FE/grain model is a promising tool to investigate the formability of multiphase materials since it provides a better understanding of local strain partitioning between the phases and eliminates the necessity of an artificial initial imperfection.

![Minor strain vs. Major strain graph](image)

**FIGURE 4.** Simulated FLD for the dual phase material

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REFERENCES