Prediction of mechanical behaviour of an ultra-thin sheet metal under non-proportional loading using a crystal plasticity model

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Abstract. A theoretical crystal plasticity model to predict mechanical responses of ultra-thin (<0.1 mm thick) sheet metal under non-proportional loading, which are difficult to measure experimentally due to premature buckling in simple shear or compression-tension test, was developed. In the model, three different dislocation density components, namely, forward, reverse and latent dislocations, were incorporated in the crystal plasticity model. The model was applied for 100 μm thick ultra-thin ferritic stainless steel sheet to predict mechanical responses under two-step tension, and the predicted results were compared with the experimental data.

1. Introduction

Recently, the proton exchange membrane fuel cell (PEMFC) has gain much attention as a promising technology to replace internal combustion engines. Among various components of the PEMFC, bipolar plate (BP) is very important part since it comprises 30-50% cost, and 60-80% weight of the PEMFC [1,2]. Stainless steels are plausible candidate for the BP application owing to their superior corrosion resistance, thermal and mechanical properties, and workability [1,3,4]. However, springback of the such thin material is a critical issue since it becomes problematic during stacking process.

To investigate the springback of the sheet metals, basic material characterization is necessarily conducted. In particular, mechanical responses under loading path changes such as loading-reverse loading should be precisely characterized. Among several experimental approaches to attain such loading path changes, shear-reverse shear test [5,6] and compression-tension test [7] are most common. However, there are technical challenges to overcome in such tests. In the compression-tension test, the strain could be hardly measured due to limited measurement area (normally, the strain is measured on the plane normal to the thickness direction). Moreover, the controlling the anti-buckling side plate would be too delicate for such thin sheet metal. In addition, buckling was observed during shear test as shown in Figure 1.
To overcome abovementioned experimental difficulties, a virtual tool to predict the mechanical response under the strain path changes were developed using crystal plasticity finite element (CPFE). To account for the strain path change effect, a recently proposed Rauch dislocation density-based model is implemented into a CPFE code. The developed model is referred to as R-CP (Rauch-Crystal Plasticity) model. The R-CP model predicted results are compared with the experimental data, and further applied to U-draw bending simulations.

2. Theoretical background
A rate dependent crystal plasticity framework based on the previous works [8–10] is adopted. General details on the basic formulation can be found elsewhere [11,12]. The core mathematical expression can be summarized as follows:

The shear rate on the α-th slip system can be expressed in power law type

$$\dot{\gamma}^{(\alpha)} = \dot{\gamma}_0 \left( \frac{\tau^{(\alpha)}}{\tau_c^{(\alpha)}} \right)^{m} \text{sign}(\tau^{(\alpha)})$$

where $\dot{\gamma}_0$, $\tau^{(\alpha)}$, $m$ are reference shear rate, resolved shear stress, and the strain rate sensitivity exponent, respectively. The slip resistance of the α-th slip system, $\tau_c^{(\alpha)}$, is represented by

$$\tau_c^{(\alpha)} = A \mu b \sum_{\beta=1}^{NS} \rho^{(\beta)}$$

where $\mu$, $b$, $\rho^{(\alpha)}$, and $A$ are shear modulus, Burgers vector, dislocation density in α-th slip system, and material constant, assumed as 0.4 in this study, respectively. The dislocation density evolves as follows

$$\rho^{(\alpha)} = \frac{1}{b} \left( \sqrt{\frac{\sum_{\beta=1}^{NS} \rho^{(\beta)}}{k_a} - k_b \rho^{(\alpha)}} \right) \dot{\gamma}^{(\alpha)}$$

where $k_a$, $k_b$ are material constants related to the dislocation generation and annihilation, respectively.

The abovementioned crystal plasticity framework can be applied to monotonic loading condition. However, it is not able to reproduce mechanical response under complex loading scenarios. In order to overcome such limitation, the phenomenological dislocation density model proposed by Rauch et al. (2011) [13] was implemented in the crystal plasticity framework. In the model, the dislocation density can be decomposed into three-components as

$$\rho^{(\alpha)} = \rho^{(\alpha)}_F + \rho^{(\alpha)}_R + \rho^{(\alpha)}_L$$

where $\rho^{(\alpha)}_F$, $\rho^{(\alpha)}_R$, and $\rho^{(\alpha)}_L$ are forward, reverse, and latent dislocation on α-th slip system, respectively.

The slip resistance of the α-th slip system in Eq. (2) is modified as

$$\tau_c^{(\alpha)} = A \mu b \sum_{\beta=1}^{NS} \left( \rho^{(\beta)}_F + \rho^{(\beta)}_R + L \rho^{(\beta)}_L \right)$$

where $L$ represents latent hardening coefficient.
Upon strain path changes, the stored dislocation during prestrain ($\rho^0_F$) is decomposed into three dislocation components as

$$
\rho_L(0) = \rho^0_F (1 - \theta^2)
\begin{cases}
\rho_R(0) = p \rho^0_F \theta^2 & \text{if } \theta \leq 0 \\
\rho_R(0) = 0 & \text{if } \theta > 0 
\end{cases}
$$

(6)

where $p$ denotes the fraction of dislocation converted into reverse dislocation upon the strain path change. $\theta$ is Schmitt factor, which is a scalar quantity characterizing the strain path change [14].

The dislocation density evolution equation in Eq. (3) is modified by following Rauch’s model as

$$
\rho_F^{(a)} = \frac{1}{b} \left( \frac{\sum_{\beta=1}^{NS} \rho_\beta^{(b)}}{k_a} - k_b \rho_F^{(a)} \right) |\gamma^{(a)}|
$$

$$
\rho_R^{(a)} = -\frac{1}{b} \left( \frac{\sum_{\beta=1}^{NS} \rho_\beta^{(b)}}{k_a} \left( \frac{\rho_R}{\rho^0_R} \right) - k_b \rho_R^{(a)} \right) |\gamma^{(a)}|
$$

(7)

$$
\rho_L^{(a)} = -\frac{1}{b} (k_b \rho_L^{(a)}) |\gamma^{(a)}|
$$

3. Experiments

100 μm thick ferritic stainless steel sheet containing ~30% of Cr for corrosion resistance was investigated in the current study.

3.1. Two-step tension test

The two-step tension test of the ultra-thin ferritic stainless steel were conducted to measure the mechanical response under the strain path changes. Pre-tension of 12% was applied to a large notched sample and the ASTM E8 sub-sized tensile samples were machined as depicted in Figure 2. The tests were conducted at strain rate of $10^{-3}$/s.

![Figure 2](image_url)

**Figure 2.** Dimension of large specimen for the first tension and ASTM E8 sub-size specimens for the second tension (See the dimensional details in [15])
3.2. X-ray measurement

In order to measure the initial texture of the investigated material, the X-ray diffraction measurement was conducted using Bruker D8 with CoKα radiation. To measure pole figures, sample was rotated 0° to 355° about the sheet sample normal direction and 0° to 80° about the sample transverse direction. The measured pole figures were then used to calculate the orientation distribution function (ODF) by MTEX software using the de la Valle-Poussin kernel and 5° half width. The ODF of the ultra-thin ferritic stainless steel sheet is shown in Figure 3.

![Figure 3. Orientation distribution function in Euler space 100 μm ferritic stainless steel sheet](image)

4. Results

4.1. Stress-strain behavior under non-proportional loading path change

The developed R-CP model is applied to predict the mechanical response under the strain path changes. The constitutive parameters for the model are determined by fitting to the stress-strain response during the monotonic tension along the RD as $k_a=13.5$, $k_b=52.0$, $\rho_0=1.8\times10^4 / m^2$. The strain rate sensitivity exponent $m$ was assumed as 0.02. The anisotropic elasticity constants of $C_{11}=242$ GPa, $C_{12}=150$ GPa, and $C_{44}=112$ GPa, and shear modulus of 80 GPa for iron were assumed. The additional parameters relevant to the Rauch’s model are determined by fitting to the stress-strain response during the two-step tension test (first tension along the RD followed by the tension along TD, or expressed as RD-TD) as $p=0.7$ and $L=1.25$. The measured and predicted stress-strain curves are shown in Figure 4. The results reveal that the R-CP model can reasonably well capture the stress overshooting and transient hardening behaviour during the two-step tension. With the identified parameters of the model, the mechanical response under the compression-tension is also predicted. The model is able to reproduce well-known behaviour in such loading condition such as Bauschinger effect, transient behaviour and permanent softening.
Figure 4. Experimentally measured and crystal plasticity model predicted stress-strain curves of 100 μm thick ferritic stainless steel sheet during tension-tension: (a) RD-RD, (b) RD-DD, (c) RD-TD, (d) TD-TD, (e) TD-DD, and (f) TD-RD, and (g) during compression-tension along the RD.
5. Conclusions
A crystal plasticity model was combined with the Rauch’s three-component dislocation density model to capture the mechanical responses under the strain path changes of the ultra-thin ferritic stainless steel sheet. The developed R-CP model was able to capture general mechanical responses under the two-step tension and compression-tension.

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