Transient Hardening and R-value Behavior in Two-step Tension and Loading Reversal for DP980 Sheet

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Abstract. The present work deals with transient hardening and R-value behavior in two-step tension and loading reversal for an advanced high strength steel DP980. Mechanical properties under the loading paths were obtained through continuous tension-compression-tension, two-step tension and loading reversal experiments. The Yld2000-2d was employed to describe the initial yielding of DP980 1.0t through conducting monotonic tests. To characterize the transient behavior, a combined isotropic/non-linear kinematic hardening model, based on the 4-term Chaboche model, was selected. The Chaboche model was calibrated with the hardening curve in continuous tension–compression-tension loading. The transient behavior from the two-step tension and the loading reversal tests was then predicted by the model. The model performance was evaluated with the comparison of transient hardening and R-value from experiments and model predictions.

1. Introduction

As design of structures has been increasingly complicated, material points experience complex loading paths during sheet metal forming processes. To understand material behavior under complex loading paths, much research has been conducted regarding changes of yielding, work-hardening rate and R-value (aka plastic strain ratio) under proportional or non-proportional loading conditions. Under the reverse-loading condition, an early-reyielding behavior, so called the Bauschinger effect [1], is observed in subsequent loading. The yield stress in the second loading is generally less than that in the first loading. With work-hardening changes in a low strain, the flow in further deformation tends to be saturated to a smaller value than that in the first loading, i.e. permanent softening [2]. For non-proportional cases, two-step tension, combination of tension in two different orientations, is generally adopted to probe the change in material properties. The yielding, work-hardening rate and R-value change during further strain in the second loading. The amount of change depends on the pre-strain and the angle difference between the loading directions of the first and the second loadings [3, 4].

To take account of changes in hardening behavior in complex loading paths, kinematic hardening models have been developed. The kinematic hardening model adopts the concept of the translation of the yield surface, the center of which is called the back-stress, to describe the Bauschinger effect and the subsequent hardening [5, 6]. For expression of complex behavior in subsequent loading, non-linear kinematic hardening was developed with summation of few non-linear terms for the back-stress [7, 8]. Most researches in modeling of the kinematic hardening under different loading paths were focused on simulating flow stresses in subsequent loading rather than the transient of the R-value.
This study investigates transient hardening and R-value behavior of DP980 sheet in two-step tension and loading reversal. A representative Chaboche kinematic hardening model [7, 8], combined with isotropic hardening, is used to confirm the model performance for simulating the transient behavior.

2. Determination of initial yield locus
The material of this study is a dual-phase advanced high strength steel (AHSS) of DP980 (1 mm thickness). To observe the mechanical responses in monotonic tension, tensile tests were conducted along three different orientations of 0°, 45° and 90° from the rolling direction. Figure 1 shows the obtained stress and R-value behavior with respect to the plastic work. The plastic work ($W_p$) was calculated by Equation (1). The DP980 sheet of this study shows anisotropic behavior as shown in figure 1(a). The R-value in figure 1(b) was determined by the plastic strain ratio of strain in width and thickness directions as described in Equation (2).

$$W_p = \int \sigma \cdot d \varepsilon_p = \int \sigma \cdot d \varepsilon_p$$  \hspace{1cm} (1)

$$R = \frac{d \varepsilon_w}{d \varepsilon_p}$$  \hspace{1cm} (2)

![Figure 1](image-url)

(a) Mechanical responses in monotonic tension: (a) flow stress; (b) R-value.

To characterize the anisotropic yielding of the DP980 sheet, plane-strain tension (PST) and disk compression tests [9-13] were additionally conducted to calibrate the anisotropic yield function Yld2000-2D [14] as shown in figure 2. These experiments were post-processed as in our earlier work, e.g., [9, 11]. The stress and the R-value data set at the plastic work of 35 MJ/m² (which corresponds to a plastic strain of about 3.5%) were used for the calibration. The calibrated parameters are listed in Table 1. The exponent used for Yld2000-2D is 6, as typical for BCC metals.

|     | $\alpha_1$ | $\alpha_2$ | $\alpha_3$ | $\alpha_4$ | $\alpha_5$ | $\alpha_6$ | $\alpha_7$ | $\alpha_8$ |
|-----|------------|------------|------------|------------|------------|------------|------------|------------|
|     | 0.921      | 0.965      | 1.016      | 0.966      | 0.993      | 0.828      | 1.007      | 1.046      |
Figure 2. Initial yield locus (solid line) calibrated with experimental data (symbols).

3. Calibration of Chaboche model
For simulating the transient hardening and R-value behavior, a combined isotropic/non-linear kinematic hardening model based on the Chaboche model, was adopted and implemented through the following equations [7, 8, 15, 16]. The constitutive law is defined by Equation (3) with the isotropic hardening term of \( R(\tilde{\varepsilon}_p) \), where \( R \) is the size of the yield surface and \( \tilde{\varepsilon}_p \) the equivalent plastic strain.

\[
f(\sigma - \alpha) = \sigma_0 + R(\tilde{\varepsilon}_p) \tag{3}
\]

The isotropic hardening indicates the size change of the yield locus with an exponential-decaying function of Equation (4). This term is used for yield surface shrinkage [16] in the present work.

\[
R(\tilde{\varepsilon}_p) = Q(1 - e^{-b\tilde{\varepsilon}_p}) \tag{4}
\]

where \( Q \) and \( b \) are fitting parameters.

For kinematic hardening, the evolution of the back-stress (\( \alpha \)) is described by the Chaboche model, using 4 terms to address the non-linear kinematic hardening, as expressed in Equation (5).

\[
d\alpha = \sum_{i=1}^{4} d\alpha_i \tag{5}
\]

The Chaboche model is based on the Armstrong-Frederic model, which in turn is a non-linear extension of Prager’s linear hardening rule [5]. Prager’s rule associates the evolution of the back-stress to the plastic strain increment. To avoid erroneous back-stress evolution under plane-stress (i.e., the accumulation of an out-of-plane back-stress, computed from the thickness strain), Ziegler’s
modification [6] of the Prager rule is adopted in this work. In the end, non-linear hardening is accomplished as represented in Equation (6).

\[
d\alpha_i = \frac{C_i}{\sigma} \left( \sigma - \sum_{i=1}^{n} \alpha_i \right) d\bar{\varepsilon}_p - \gamma_i \alpha_i d\bar{\varepsilon}_p
\]  

(6)

As an experimental observation, a continuous tension-compression-tension test was performed to obtain the hardening behavior. This experiment was performed on a custom tension-compression testing machine of 50 kN force capacity, using an antibuckling device using comb-shaped teeth, to offer continuous support to the specimen throughout loading (see [17], based on the design described in [16]). The specimen was elongated up to 5% engineering strain and compressed back to 0%. It was then elongated again up to the fracture. Using this experimental result, the Chaboche model was calibrated as shown in figure 3. The fitted curve (solid-line) shows very good agreement with the experiment (symbol). The calibrated parameters are listed in Table 2.

![Figure 3](image)

**Figure 3.** Hardening behavior in continuous tension-compression-tension and model calibration. Shown in parenthesis is also the equivalent plastic strain at the end of the loading.

| $i$ | $C_i$ (MPa) | $\gamma_i$ (MPa) | $b$ | $Q$ (MPa) | $\sigma_0$ (MPa) |
|-----|-------------|------------------|-----|-----------|----------------|
| 1   | 300000      | 3000             |     |           |                |
| 2   | 110000      | 500              |     | 200       | -140           |
| 3   | 1500        | 22.5             |     | 200       | 430            |
| 4   | 30000       | 80               |     |           |                |

### 4. Model performance

Two-step tension and a loading reversal test were additionally designed to confirm the performance of calibrated Chaboche model for simulating transient hardening and R-value behavior. For the two-step tension test, a specimen was elongated up to 3.2% along the rolling direction (0°) first. Another tensile specimen was cut from the elongated specimen in the first step and was elongated up to fracture along
90° in the second step. Regarding the loading reversal test, a specimen was firstly compressed by 5% along 0° direction. The compressed specimen was elongated up to fracture along 0° direction in the second step. Figure 4 shows the results of the two-step tension and the loading reversal with monotonic tension and compression curves experimentally obtained. In figure 4(a), the transient hardening behavior is observed in the early part of the second loading while the permanent softening behavior is slightly observed regarding further deformation. On the other hand, the loading reversal case in figure 4(b), the early re-yielding and the permanent softening are more remarkable compared to the two-step tension.

![Figure 4](image-url)  
**Figure 4.** Experimental observation of hardening behavior of DP980 in: (a) Two-step tension; (b) Loading reversal. Shown in parentheses are also the values of the equivalent plastic strain at the end of each loading.

With the calibrated Chaboche model, the hardening and R-value behavior in the two-step tension and the loading reversal were predicted as shown in figure 5 and figure 6, respectively. For both cases of the two-step tension and the loading reversal, the transient R-value behavior were well-predicted by the model. Related to the hardening behavior, however, the predicted stresses are little bit different from the experimental results although 4 non-linear terms were adopted. It seems that the loading history in compression must be considered more carefully to enhance the model performance since the particular DP980 sheet shows asymmetric behavior as shown in figure 6(a). The constitutive framework adopted in this work does not allow for asymmetric yielding.

The fact that the predicted R-value behavior in both two-step tension and loading reversal is showing very good agreement with the experimental results can lead to the conclusion that the shape of yield locus in these regions is represented quite well. According to the loading direction, the back-stress evolves resulting in the translation of the yield locus so that complex transient behavior in R-value and hardening can be simulated by the model.
5. Summary and future work

This paper investigates transient hardening and R-value behavior in two-step tension and loading reversals for a DP980 sheet. The anisotropic yield function Yld2000-2D is selected and calibrated to represent initial yielding. To construct a combined isotropic/non-linear kinematic hardening, 4-terms Chaboche model was adopted and calibrated with various monotonic experiments and a continuous tension-compression-tension test. For confirming the model performance, two-step tension (tension in 0° and tension in 90°) and loading reversal (compression in 0° and tension in 0°) tests were conducted. The calibrated model was then used for simulating the transient behavior. Overall predictions for hardening and R-value are showing good agreements with the experimental results. To enhance the performance to describe the hardening and the R-value simultaneously, it would be necessary to consider the loading history in compression more carefully. In future work, the authors will adopt other advanced models, e.g. distortional hardening model, to capture transient behavior of both hardening and R-value under various loading paths.
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