Simulation of springback in cyclic wipe-bending

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Abstract. This paper proposes a bending method to measure the robustness of advanced material constitutive models, which are developed aiming to precisely express material responses including the Bauschinger effect, permanent softening, etc. Such constitutive models, in general, require multiple sophisticated material tests, e.g. cyclic uniaxial tension-compression, followed by appropriate numerical optimizations to identify corresponding material model parameters. These tests, for example, intrinsically require anti-buckling measures for specimens that can lead to redundant frictional forces and biaxial effects. Besides, the strategy for the optimization of material parameters or the selection of elastic modulus model is also an important point to influence the final performances. In an effort to provide more robust reliability for springback simulation results, a wipe-bending tool enabling cyclic load reversals has been developed as an intermediate validator positioned between the role of the cyclic uniaxial tension-compression and that of the U-drawbending. Predicted springback results employing the Yoshida-Uemori model have shown that this approach can be considered as an effective way to confirm both the reliability of material model parameters and the capability of a selected constitutive model in a part development or tooling stage.

1. Introduction

High strength steels for automobile structural parts often lead to unwanted deterioration of shape fixability due mainly to springback in cold forming. Concerning this, FE analyses are being widely used, employing advanced constitutive descriptions such as the Yoshida-Uemori model [1,8], Barlat’s homogeneous anisotropic hardening model [2], etc. as well as the works of Chaboche [3,4] to precisely express complicated hardening behavior of the steels.

These constitutive models, providing accurate springback predictions, require multiple elaborate material tests to identify their material model parameters, which are closely related to load reversals or the change of loading in various directions [2]. While carrying out such tests, and doing subsequent data treatments, unintended uncertainties or redundant data can be produced by certain sources such as uneven distribution of material properties, the complexity of reference data acquiring (e.g., the correction of the friction and biaxial effects from anti-buckling plates [1,10] attached to tension-compression specimens), the following numerical optimizations for material model parameters, etc.

Regarding this, a cyclic wipe-bending tool has been introduced in order to help confirming not only the reliability of acquired material model parameters but also the performance of selected constitutive descriptions. This unique bending tool, specifically, aims to generate an elastic recovery zone only by bending moment after a cyclic loading, unlike the U-drawbending [5] by which the superposition of
tensile stress is also allowed, thus diminishing the bending moment. Then an application with a DH780 steel sheet is shown together with corresponding FE simulations as described in the following sections.

2. **Springback in cyclic wipe-bending**

Wipe-bending (also, L-bending) is widely used in the automobile industry as a process to shape straight flanges in parts. Tools are basically consisted of wiping die, a punch and a pressing pad. This tool is useful to study the effect of tool conditions: as it is seen in other cases, the springback in wipe-bending is also largely influenced by the radius of die, tool clearance, pad pressure, punch radius, etc. [13]. In this paper, an improvement on the conventional tool concept has been made to add a cyclic loading function as follows.

2.1. **Cyclic wipe-bending device**

This new tool consists of a pair of rolling pins (rolls) and another pair of bending dies to perform a serial bending including load reversals, for which no unclamping and reclamping of the specimen are required.

20-mm-diameter rolls are mounted through four roller bearings inside the surrounding rigid steel frame with a fixed distance (100 mm) between the axes of the two rolls as shown in figure 1. These synchronized rolls travel vertically by a connected actuator according to programmed forward-reverse bending cycles. The upper and lower bending dies, corner radii (R<sub>d</sub>) of 10 mm, tightly hold the rectangular specimen (40 mm × 140 mm) with two fastener bolts. The gap between the outer surfaces of the rolls and the die wall is fixed as 3 mm. Figure 2 schematically explains the way the specimen is bent by the lower and upper rolls for bending up and down, respectively. Here, the specimen undergoes springback in a gradual manner because either the upper or the lower roll maintains its contact with the specimen while the rolls are moving along the opposite direction. This gradual springback has to form the required opening angle in order for the approaching roll to successfully intrude into the narrow open space between the specimen and the die walls in the initial stage of the bending reversal.

![Figure 1](image-url)  
*Figure 1. Cyclic wipe-bending device (left) and its side view with dimensions (right)*

Through this way, the system can repeat a given number of bending reversals unless the specimen concerned shows enough amount of springback; in other words, in case the specimen is relatively thick or its strength very low (especially, mild steel cases).
A hot dip galvanized 780 MPa (minimum tensile strength) steel, DH780, sheet was used as the specimen material. The thickness of the specimen is 1.5 mm, of which the ratio between the specimen thickness and the tool gap (3 mm) leads to 0.5. The rolling direction of the specimen is perpendicular to the bending axis. Here, DH steel is a new concept of DP steel that improves formability by introducing a small amount of retained austenite into the microstructure, and thus can be applied to various cold stamped automobile body parts with complicated geometries.

Figure 3 presents the specimens produced by Forward (bending down), Forward (bending down)-Reverse (bending up) and Forward-Reverse-Forward bending processes involving zero, one and two load reversals, respectively. Three specimens were used for each bending condition to consider the deviation of the test data. Note that a negative sign of Z-coordinate is given only to the Forward-Reverse case in figure 3 for convenience because the final tool movement is the opposite of the others, leading to an upward flange.

Figure 2. Schematic explanation of cyclic wipe-bending process

Figure 3. Zn coated DH780 Specimens after single forward bending (left), forward-reverse bending (center), and forward-reverse-forward bending (right)
In this study, the springback is simplified as the angle between the vertical reference line along Z coordinate and the line representing the straight portion of the flange region as explained in figure 3. This is not the true springback but an apparent measure because the flange at the end of bending is not exactly aligned with the reference line due to the tool clearance, which is larger than the specimen thickness. Consequently, almost the same springback angles were successfully reproduced in each specimen group subjected to the given bending conditions. These experimental results are summarized in figure 11 in section 3.

2.2. FE simulation
The developed wipe-bending process introduced in the previous section was implemented through a commercial FE software, Pam-Stamp2G™ [6], as depicted in figure 4, employing the Belytschko-Tsay shell [7] for the element type of the specimen. The initial size of the element, the number of integration points through thickness and the vertical velocity of the rolls were optimized as 1 mm × 1 mm, seven and 2 m/sec, respectively, through preceded springback sensitivity analyses. A negligibly low friction coefficient (0.001) was applied to the contact of the roll and the specimen surfaces to simplify the lubricating effect by the bearings.

The Yoshida-Uemori model (Y-U model) [1,8], a two surface model which is associated with the motions of both yield and bounding surfaces, by which cyclic plasticity relevant hardening behaviours can be precisely expressed, was considered. The two yield surfaces in the Y-U model are described by $f = \Phi(\alpha - \alpha) - Y = 0$ and $F = \Phi(\alpha - \beta) - (B + R) = 0$ for the yield and the bounding surfaces, respectively. In this, $f$ moves only kinematically while $F$ facilitates mixed isotropic-kinematic hardening. Here, $\alpha$ and $\beta$ are the back stresses of the yield and bounding surfaces, giving the relative kinematic motion of $f$ and $F$ as $\alpha(= \alpha - \beta)$. $Y$ represents the radius of $f$, and $B$ and $R$ are the initial size and the isotropic hardening (IH) component of $F$, respectively.

Barlat’s anisotropic yield surface model, the YLD2000-2d, was incorporated into the Y-U model to describe the plastic anisotropy ($r_{04}$, $r_{45}$ and $r_{90}$ of 0.789, 1.001 and 1.072, respectively). More detailed information to the Y-U and the YLD2000-2d can be found in the relevant works [1,8,9]. Then all material model parameters were numerically identified as listed in tables 1 and 2, associated with required material tests: namely, uniaxial tension-compression-tension (T-C-T) tests, tensile tests for r-values, etc.

![Figure 4. FE model (left) and its deformed configuration after forward bending (right)](image-url)
Meanwhile, the parameters for the elastic modulus model (appeared in the bottom of table 1) as a function of plastic strain (prestrain) proposed by Yoshida et al. [8], 
\[ E(\varepsilon_p) = E_0 - (E_0 - E_a)[1 - \exp(-\xi \varepsilon_p)] \]
were identified by a direct fitting to the experimental unloading elastic moduli data measured along the rolling direction. In this, the stress points used to extract every average elastic modulus (chord modulus) required to constitute \( E(\varepsilon_p) \) were taken at each load reversal from tension or compression state produced by another cyclic T-C-T test with a load reversing increment of 0.02. In other words, a chord modulus in this paper is the slope of a line bisecting the narrow loop (due to the nonlinear nature of elastic modulus) of stress-strain curve, formed while reversing load. This loop is also introduced as the so-called Quasi-Plastic-Elastic (QPE) strain [10,11]. This choice leads to the largest elastic recovery in a given stress drop in a course of unloading.

Here, the specimens for all the experimental T-C-T tests were specially designed to effectively adapt to their anti-buckling plates that covered the entire surfaces of the parallel regions of the specimens (gage length: 20 mm, width: 15 mm).

Figures 5 and 6 present the performances of these optimized material model parameters incorporated into the Y-U model in the case when they are applied to a single element FE model, of which its size is 1 mm×1 mm, for the T-C-T test and the tensile tests regarding r-values along three different test directions. The Bauschinger effect followed by the non-linear kinematic hardening during the compression was appropriately captured by this simulation in figure 5.

### Table 1. Material model parameters for Yoshida-Uemori model regarding DH780 steel

| Description                  | Parameter | Typical Range | Value  | Unit  |
|------------------------------|-----------|---------------|--------|-------|
| Yield surface (f)            | \( Y_0 \) |               | 0.4642 | GPa   |
|                              | \( C_1 \) | 200–2000      | 104.0  |       |
|                              | \( C_2 \) | 100–800       | 131.8  |       |
|                              | \( \varepsilon_{p, \text{ref}} \) |            | 0.005  |       |
| Bound surface (F)            | \( B_0 \) |               |        |       |
|                              | \( B_0 \cdot Y \) | 0.1Y–0.5Y | 0.0002 | GPa   |
|                              | \( R_0 \) |               | 0.0001 | GPa   |
|                              | \( b_0 \) | 0.1Y–0.5Y     | 0.07557| GPa   |
|                              | \( M \) | 2–30          | 6.224  |       |
| Hardening law (Swift type)   | \( K \)  |               | 2.784  | GPa   |
|                              | \( e_0 \) |               | 0.0008819 |     |
|                              | \( N \)  |               | 0.03641 |     |
| Swift/Voce Weight            | \( m \)  |               | 1      |       |
| Non-IH                       | \( h_2 \) | 0–1           | 0      |       |
|                              | \( r_0 \) | 0.01          | 0.00001| GPa   |
| Elastic modulus              | \( E_0 \) |               | 207    | GPa   |
|                              | \( E_a \) |               | 136.7  | GPa   |
|                              | \( \xi \) |               | 23.1   |       |

### Table 2. Optimized parameters for YLD2000-2d

| \( m \) | \( \alpha_1 \) | \( \alpha_2 \) | \( \alpha_3 \) | \( \alpha_4 \) | \( \alpha_5 \) | \( \alpha_6 \) | \( \alpha_7 \) | \( \alpha_8 \) |
|---------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|
| 6       | 0.9094         | 1.0644         | 1.0565         | 0.9909         | 1.0106         | 0.9445         | 1.0107         | 1.0299         |
Overall, the one element shows good agreements with the experiments in this basic validation stage. However, a visible deviation from the experiment still remains: especially, a slightly higher hardening rate of the predicted curve is clearly observed in the compression stage (figure 5).

![Figure 5. Simulated T-C-T curve](image)

![Figure 6. Simulated r-values of DH780](image)

### 3. Results and Discussions

Figure 7 shows that the range of the strain change on the surfaces of the element at position P subjected to bending is similar to that of the T-C-T curve in figure 5, which are ± 0.068 and ± 0.060 for the former and the latter, respectively. In this, the coordinate X defined in the local (element) frame, which is initially aligned to the fixed global frame, is parallel to the longitudinal direction of the blank. Note that these stress and strain components are manually converted from those projected to the fixed global frame, based on the coordinate transformation rule. Besides, the shear components are ignored in this operation due to lack of related information from the software. This assumes that the monitoring element located at P undergoes negligible amount of shear.

![Figure 7. Change in stress-strain in material coordinate X at P during springback after Forward bending](image)

The corresponding axial stress along X in the local frame is relieved from 0.575 to -0.149 GPa on the outer fiber (outer surface), and is from -0.568 to 0.236 GPa on the inner fiber (inner surface) of the monitoring position, P. The stress in the membrane (the middle fiber), meanwhile, remains almost unchanged compared to those on the surfaces.
The resultant springback angle corresponding to this stress change (figure 7) after Forward bending is depicted in figure 8, and those after Forward-Reverse and Forward-Reverse-Forward bending processes are shown in figures 9 and 10, respectively.

**Figure 8.** Springback after forward bending

**Figure 9.** Springback after forward-reverse bending

**Figure 10.** Springback after forward-reverse-forward bending

The springback trend, the change in the springback angle increases as the number of bending increases, is reasonably captured by the simulation as summarized in figure 11 in accordance with the sluggish material hardening in a large deformation stage. The range of the discrepancy from the experimental springback angles is -1.0 to 1.5 degree. The simulation leads to a larger increasing trend in springback angle as the number of bending increases. The similar discrepancy observed in the one element validation (section 2.2)—namely, the slightly higher hardening rate—can partly account for this difference. Predicted springback can also be influenced by not only the degree of fitness for an experimental cyclic flow curve depending on its parameter optimization strategy, but also by the expression of unloading elastic modulus. Especially, the way to define elastic modulus is a crucial factor.
to elastic recovery due to the nonlinear nature of elastic modulus, i.e., the QPE [10,11]. The chord modulus used in this work is, however, linear, and its slope can be chosen by the selection of the stress points in a stress-strain loop of unloading/reloading. The choice of this paper expects the largest elastic recovery as explained in section 2.2.

In addition, a recent study [12] showed that the prestrain dependent elastic modulus can also be modeled as function of testing direction. These aspects might be considered as a topic of further study with this bending tool.

![Figure 11. Comparison of springback angles (F: Forward, F-R: Forward-Reverse, F-R-F: Forward-Reverse-Forward)](image)

### 4. Conclusions
A cyclic wipe-bending tool that can impose multiple bending reversals on sheet specimens is proposed for advanced material models to be applied more reliably. As the initial application of this device, the evaluations of springback angles after Forward, Forward-Reverse and Forward-Reverse-Forward bending processes were successfully carried out experimentally. Then, corresponding FE simulations were also implemented adopting the Yoshida-Uemori model [1,8] combined with the YLD2000-2d [9] employing numerically identified material model parameters, referring to the uniaxial tension-compression-tension response of a DH780 steel sheet. As a result, the predicted springback angles showed a good agreement with the experiments, and the sluggish trend in the springback angle development, which increases as the number of the bending reversal increases, was also properly captured by the simulation, though a small amount of discrepancy still remained due to various aspects, e.g., the strategies for the hardening parameter optimization, elastic modulus modelling, etc.

Nevertheless, it is worth using the developed procedure to check the performance of advanced material models specialized for springback evaluations such as the Chaboche model [3, 4], the Yoshida-Uemori model, Barlat’s homogeneous anisotropic hardening model [2], etc., especially in need of an additional validation before applying them to full-scale practices.

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