Experimental and numerical study of springback effect of advanced high strength steel in a V-shape bending

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Abstract. Advanced high strength (AHS) steel sheets are increasingly used for the production of various automotive structural parts. The components of new lightweight vehicles have very complex shapes, for which more precise forming procedures are required in order to achieve a desired geometry. Hereby, springback occurrences of such AHS parts are often the most critical concern. In this work, it aimed to investigate springback effects of the AHS steel grade 980 in a V-shape bending process. Experimental bending test and its corresponding FE simulations were conducted. The Hill’48 and Barlat89 yield criteria, and the Yoshida-Uemori (Y-U) kinematic hardening model were applied. The yield function parameters were obtained from the tensile tests of samples in various orientations. The Y-U model parameters were determined from a cyclic tension-compression test and were afterwards calibrated with the 1-element simulation. The resulted bend angles measured from the experiment and predicted by FE simulations using the different models were compared and evaluated. For the bending in this work, the Hill’48 and Barlat89 models showed the predictive errors of springback angle 1% and 2% higher than the Y-U model, respectively. The accuracy of springback prediction could be improved by the Y-U model using C1 and C2 parameters around 1%. In addition, effects of sheet thickness and punch radius on the springback were afterwards studied and discussed by using the Y-U model.

1. Introduction
Presently, part manufacturers in the automotive and related industries using the metal forming technologies have strongly targeted to spend shorter time for die design and tryout. More precise analytical and numerical approach are thus needed for improving the quality and reducing defects of forming parts. FE simulation has become an important tool in the die design for predicting the results of employed forming processes, especially the springback occurrence [1]. Critical forming parameters as die shape, forming procedures in detail could be well optimized by using the FE simulations. Advanced high strength (AHS) steel sheets have been continuously developed and widely applied for various automobile components, in which both enhanced lightweight and crashworthiness features can be reached simultaneously [2]. Such AHS steel sheets exhibited largely complex springback phenomena. Therefore, FE simulation should incorporate all relevant material characteristics including the Bauschinger effect of studied AHS steel sheets in order to attain more accurate predictions [3-5]. Different types of yield functions and kinematic hardening models like Hill’48, Barlat89, Barlat2000 models [6-7], mixed isotropic-kinematic hardening model, Geng-Wagoner hardening model, Chaboche kinematic hardening model [8-10] have been introduced for each concerned materials. The Yoshida-Uemori (Y-U) kinematic hardening model [11-12] was developed, in which the effect of backstress was incorporated to capture the transient Bauschinger effect of deformed material. It was
shown that the Y-U hardening model exhibited a great capability for describing the material elastic recovery of different sheet metals. Various experiments and FE analyses of forming tests were performed for investigating the springback effect by using the Y-U model in [13-14]. It was seen that the prediction of springback by the Y-U model required a cyclic stress-strain curve with sufficient compressive strain so that its parameters could be accurately obtained [15]. However, gathering of such experimental material data has been still limited for the industry. Therefore, conventional material models are hereby favored, by which the correctness of the corresponding FE results in some cases could be arguable. The predictive accuracies of such simple models and the Y-U model should be illustrated in comparison for a better evaluation of prediction errors occurred due to both models.

In this work, the V-shape bending of the AHS steel sheets grade 980 was investigated. Both experiments and FE simulations were carried out for the specified forming process. For the simulations, the Hill’48, the Barlat89 and the Y-U models were applied. Uniaxial tensile tests and cyclic tension-compression tests were performed for obtaining the necessary material parameters of the used models. FE simulations of an 1-element model were conducted and the result was compared with the experimental data in order to calibrate obtained parameter sets of the Y-U model. From the V-bending simulation, springback angles of formed samples predicted by different yield functions were compared with the experimental results and then the errors of each model were presented. Furthermore, the effects of the parameters C1 and C2 of the Y-U model were studied. Finally, punch radius and sheet thickness were varied and their effects on the springback of samples were presented.

2. Materials testing and model parameters

2.1. Tensile test
The material examined in this work was a AHS steel sheet grade dual phase (DP) 980 with an initial thickness of 1 mm. The chemical composition of the steel was a typical low carbon steel, as provided in Table 1. The microstructure of the DP steel exhibited martensitic islands finely distributed in a ferritic matrix with approximately the same phase fractions, as shown in Figure 1. Uniaxial tensile test was carried out for characterizing the anisotropic plastic behavior of the investigated steel. The tensile specimens according to DIN EN 10002 standard with a gauge length of 50 mm were prepared.

| Steel grade | C   | Si  | Mn  | P   | S   | Cr  | Al  | Ti  |
|-------------|-----|-----|-----|-----|-----|-----|-----|-----|
| 980         | 0.1510 | 0.4750 | 2.1500 | 0.0046 | 0.0102 | 0.0160 | 0.0095 | 0.0256 |
Figure 1. Microstructure of the investigated DP steels grade 980.

The tensile properties including the elastic modulus (E) of the steel subjected to different loading directions with regard to the rolling direction were determined from the tensile tests and are then summarized in Table 2. The yield strength (YS) of sample from the 0-degree direction showed was highest, while that of sample from the 90-degree direction was lowest. The ultimate tensile strengths (UTS) of all samples were approximately similar. However, the 45-degree sample exhibited the largest uniform and total elongations, whereas the 0-degree sample showed the highest r-value. These basic material data in Table 2, especially the r-values, were used as the material parameters of the Hill’48 and Barlat89 yield criteria. Note that the material constant M of 6 was applied for the Barlat89 model. The Hill’48 and Barlat89 yield functions were used in this work, since they represented the isotropic hardening model coupled with different descriptions of anisotropic yielding. The Hill’48 model parameters were commonly based on r-values along 0, 90 and 45° to the rolling direction, while the Barlat89 model parameters required the yield stress or the r-values only along 0° and 90° to the rolling direction. Additionally, the experimentally obtained true stress–true strain curves of the used steel in varying directions are depicted in Figure 2(a). The material hardening parameters K and n of 1352 and 0.08, respectively, were determined by the power law from the flow stress curve of the 0-degree direction sample.

Table 2. Mechanical properties of examined steel grade 980 obtained by tensile test.

| Direction | E (GPa) | YS (0.2% Offset) (MPa) | UTS (MPa) | % Elongation Uniform | % Elongation Total | r-value |
|-----------|---------|------------------------|-----------|---------------------|-------------------|---------|
| 00 deg    | 209.87  | 745.47                 | 1013.21   | 7.64                | 13.99             | 1.32    |
| 45 deg    | 206.35  | 732.82                 | 1014.75   | 7.71                | 15.13             | 1.22    |
| 90 deg    | 204.69  | 709.96                 | 1016.43   | 7.56                | 14.94             | 1.29    |
| Average   | 206.97  | 729.42                 | 1014.80   | 7.67                | 14.69             | 1.26    |
2.2 Cyclic test
The cyclic tension-compression tests of the investigated steel were conducted up to the total tensile and compressive strains of about 0.10, in which a saturation state of the gathered re-loading stress-strain response was achieved. Hereby, a special fixture was designed and employed to prevent the buckling of test sheet samples. More details can be referred to the previous work in [15]. A Zeplon spray was applied to reduce friction between clamping plates and test specimen. The local displacements of loaded specimens were measured by a contactless digital image correlation (DIC) system. The true stress-true strain curve obtained from the cyclic tension-compression tests is presented in comparison with the monotonic tensile curve in Figure 2(b). By means of the true stress-strain curves from both monotonic and cyclic tests, the model parameters of the Y-U hardening model could be derived. It is noted that two types of the Y-U model, namely, a single C parameter and two C parameters were considered and the obtained parameter sets of both types are summarized in Table 3. These Y-U parameters were identified similar to that was done in [13]. In addition, the parameters, which described the relationships between elastic modulus and applied plastic strain, were also determined, as given in Table 4. Note that the geometry of the cyclic sample differed from that of the standard sample used in the tensile test. The standard sample was modified for the cyclic test according to the designed fixture. More details about the sample dimension could be found in [15].

Table 3. Determined material parameters of the Y-U model for the investigated steel grade 980.

| Materials model | Y (MPa) | B (MPa) | k  | b (MPa) | $R_{sat}$ (MPa) | $C_1$ | $C_2$ | $h$ |
|----------------|--------|--------|----|---------|----------------|------|------|-----|
| Y-U_C1         | 729.42 | 914.24 | 14.19 | 34.32 | 288.49 | 150 | -    | 0.5 |
| Y-U_C1, C2     | 729.42 | 914.24 | 14.19 | 34.32 | 288.49 | 65  | 40   | 0.5 |

Table 4. Parameters for the relationship between elastic modulus and plastic strain.

| $E_0$ (GPa) | $E_{sat}$ (GPa) | $h$ |
|------------|----------------|-----|
| 206.97     | 128.40         | 14.19 |
3. **V-shape bending test**

The experimental V-shape bending tests of the steel grade 980 were carried out. A schematic view of designed tools including dimensions of the bending test is demonstrated in Figure 3(a). The initial blank size of 40 mm in width, 100 mm in length and thickness of 1 mm was used. The aimed bending angle was 90°. After the experiments, final geometries of formed parts were measured by means of a contactless optical system. Then, the results were used for evaluating the occurred springback magnitude. The angles 1 and 2 of the bended sample, as illustrated in Figure 3(b), were considered here.

![Figure 3](image_url)

**Figure 3.** (a) Schematic view of tools for the V-shape bending test, (b) measured angles for evaluating the springback of sample after forming and (c) FE model for the V-shape bending test.

4. **FE simulations**

Firstly, FE simulations of tension-compression behaviour of the investigated steel were performed in LS-DYNA by using a single plane stress shell element model. The model was a square element with a size of 1x1 mm. The left-bottom node was constrained in both horizontal and vertical direction, while the right-bottom node was constrained only in the vertical direction. The displacements in positive and negative vertical direction were applied to the top side of the element. The element formulation type 2 (Belytschko-Tsay) with one integration point through thickness was used. For the 1-element simulation, the kinematic hardening material model (MAT_125 model) in LS-DYNA [16] or the Y-U model was defined. Additionally, FE simulations coupled with the Hill’48, Barlat89 and Y-U model were carried out for the V-shape bending test. The die, punch, binder, blank sample and boundary conditions for the simulations were modelled according to the experimental setup. The blank was meshed using a shell element, while all other tool components were defined as a rigid body. The number of integration points over the sheet thickness for the V-bending simulations was 5. The FE model for the V-shape bending test is depicted in Figure 3(c). The experimentally determined materials parameters of the used model were applied in the simulations. Afterwards, the springback angles of bended samples were calculated by the FE simulations and compared with the measured results. Finally, FE simulations using the Y-U model were conducted for the sheet thicknesses of sample of 1, 1.2, and 1.4 mm and punch radius of 2, 6, and 10 mm and the springback results were compared and discussed.
5. Results and discussion

For the verification of the material parameters determined from the monotonic tension and tension-compression test of the applied models, the cyclic stress-strain curves from the corresponding 1-element simulations were compared with the experimental curve in Figure 4. It can be seen that the simulation coupled with the Y-U kinematic hardening models could predict the cyclic stress-strain curves, which were fairly agreed with the experimental response, especially in the reversal region where the Bauschinger effect played a vital role. It implies that the Y-U model parameters identified from the experiment in this work were acceptable. However, it is noted that the parameter C of the Y-U model governed the rate of the kinematic hardening with regard to the range of transient Bauschinger deformation of the reversal stress–strain curve. Obviously, the Y-U model with C1 and C2 parameters generally exhibited a better description of the overall stress-strain curves than that with a single C parameter. In addition, both Hill’48 and Barlat89 isotropic hardening models could not well represent the unloading behaviour of material.

![Figure 4](image_url)

**Figure 4.** Cyclic stress-strain curves calculated by the 1-element FE simulations using different models in comparison with the experimental curve.

After tool removal in the simulations of V-shape bending test, the bend angle of formed sample was predicted and then compared with the experimentally measured data in Figure 5. The presented final bend angles were obtained from the simulations coupled with different material models. The percentage errors of the calculated angles were provided for representing the predictive accuracies of each model. Generally, it was obvious that the Y-U kinematic hardening model could more precisely predict the springback effects of AHS steel sheets grade 980 after the V-shape bending than other used model. Furthermore, the result of the Y-U model with C1 and C2 parameters was closer to the experimental one than that with a single C parameter. The simulation using the Barlat98 yield function showed the maximum deviations of predicted bend angles with the error difference of up to 2%. It is noted that the material model without consideration of the unloading behaviour of concerned material could lead to significantly underestimated springback angles. Figure 6 depicts the results from a best-fit function for the final shapes of formed samples obtained from the experiment and predicted by FE simulations using the different material models. It is seen that the Y-U model with C1 and C2 parameters certainly predicted the smallest overall shape deviations.
Figure 5. Bend angles determined from the experiments and predicted by FE simulations using different material models.

Figure 6. Comparisons of the final shapes of bended sample from the experiment and FE simulations coupled with the (a) Barlat89, (b) Hill48 and (c) Y-U models by using a best-fit function.

The predicted plastic strain distributions on bended samples at the final springback forming stage from FE simulations using various models before calculation were noticeably different, as depicted in Figure 7. It was found that the occurred critical stains obtained from the Y-U model, especially at the bend radius and flange area were slightly higher than the other models. This was due to different load-unloading behaviors described by the used models. For such bending process, in which a small unbending took place at the flange, the Y-U model was beneficial to predict the deformation at the flange. In addition, the effects of sheet thickness and punch radius in the V-shape bending test were studied by using the FE simulations coupled with the Y-U model. The predicted bend angles by using different sheet thicknesses of 1, 1.2 and 1.4 mm and punch radii of 2 (R2), 6 (R6) and 10 (R10) mm are compared in Table 5. Note that the angle 1 and angle 2 as design were 45°. It is seen that the increased thickness of sample led to considerable larger bend angles for all used punch radii that implied increased springback magnitudes. On the other hand, increasing punch radius of the V-shape
bending tool also caused larger final bend angles and consequent springback values. However, it must be noted that the small punch radius of 2 mm provided the samples with the bend angles smaller than the design angle (spring-go), whereas the larger punch radii of 6 mm and 10 mm exhibited the bend angles larger than that design one (spring-back). These design factors should be carefully taken into account when performing a forming process including bending step. Experimental V-shape bending tests with varying sheet thicknesses and punch radii will be performed in the future in order to further investigate the predictive errors of each model.

![Plastic strain contours](image)

**Figure 7.** Comparisons of the plastic strain contours of bended sample obtained by FE simulations coupled with the (a) Barlat89, (b) Hill48 and (c) Y-U models before springback calculation.

**Table 5.** Predicted bend angles of V-shape samples by using different sheet thicknesses and punch radii from FE simulations coupled with the Y-U model.

| Thickness (mm) | Resulted bend angle (degree) |
|---------------|------------------------------|
|               | 1.0                          | 1.2                          | 1.4                          |
| Punch radius - R2       | 43.36                       | 44.39                       | 44.76                       |
| Punch radius - R6       | 45.65                       | 46.29                       | 46.32                       |
| Punch radius - R10      | 46.93                       | 48.76                       | 48.18                       |

**6. Conclusions**

In this study, springback effects of the AHS steel sheet grade 980 subjected to the V-shape bending test were investigated. Both experiments and FE simulations using different yield functions and hardening models, namely, Barlat89 and Hill’48 and Y-U model were performed. The material parameters of the used models were directly determined from the monotonic tensile tests in different sample orientations and cyclic tension-compression tests. In addition, the Y-U model parameters were afterwards calibrated using the 1-element simulation and comparison between the experimental and numerical cyclic curves. From the V-shape bending test, it was found that the accuracy of predicted bend angles for the investigated 980 steel by the Y-U model was higher than the Hill’48 and Barlat89 models around 1% and 2%, respectively. On the other hand, the results of the Y-U model using $C_1$ and $C_2$ parameters were more precise than that using a single C parameter. Moreover, the effects of sheet thickness and punch radius on the springback occurrence in the V-shape bending process were presented and the FE predictions will be compared with the experimental results in the future.
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