Study of Effect of Varying Clearances on the Springback of Advanced High Strength Steel Sheets

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Abstract. The springback of metal sheets shows a significant effect on the forming results of automotive structural parts. The components of new vehicles often have complex shapes, for which more precise forming procedures are required in order to achieve their desired geometries. Such springback occurrence is highly critical in the case of advanced high strength (AHS) steels. In this work, a V-shape stamping test was carried out for the AHS steel sheets grade 980 with an initial thickness of 1 mm. In parallel, the corresponding finite element (FE) simulations were conducted. Hereby, the Yoshida-Uemori (Y-U) kinematic hardening model was applied for describing the plastic deformation and elastic recovery of material. The parameters of the Y-U model were obtained from a tension-compression test and afterwards verified by using the 1-element model. The predicted bend angles of the formed samples fairly agreed with the experimentally measured results. Furthermore, the effect of defined die clearance at the corner of the formed sample on the magnitude of springback was numerically studied. It was found that the reduction of clearance of 10% led to obviously decreased shape deviations in the V-shape forming test.

Keywords: Springback effect; AHSs; Y-U model; FE simulations

1. Introduction

Advanced high strength (AHS) steel sheets are important materials for making automotive structural parts. In the sheet metal forming industries, it is strongly aimed to shorten time for die design and try out in order to achieve the competitiveness. Therefore, accurate numerical simulations are needed for improving the quality and reducing critical defects of produced parts. AHS steel sheets have been developed and thus increasingly used for the automotive components, by which both enhanced
lightweight and crashworthiness characteristics can be reached simultaneously. Generally, the microstructure of AHS steel sheets is predominantly composed of soft ferritic matrix and hard martensitic particles. The hard martensitic phase provided substantial strength, while the soft ferrite phase was associated with good ductility [1]. During the die design, FE simulations have been commonly employed to predict the springback occurrence of stamping parts [2]. The springback effect of such AHS steel sheets was much larger than that of the mild steel sheet. For a more precise description of the springback effects of AHS steel sheets, the Bauschinger effect should be taken into account in the material model [3-4]. The FE analysis is a practicable and effective tool for springback prediction, but it is very sensitive to the applied constitutive models and numerical tolerances [5]. The Yoshida-Uemori (Y-U) kinematic hardening model [6,7] has been introduced, in which the effect of backstress was incorporated in order to capture the transient Bauschinger effect. It was reported that the Y-U model exhibited a great capability for representing the material elastic recovery of different sheet metals. Experimental and FE analyses coupled with the Y-U kinematic model were performed for different forming tests and subsequently the springback results were compared [8, 9]. It was seen that the Y-U hardening model required a cyclic stress-strain curve with a sufficient compressive strain of examined material so that accurate parameter sets could be obtained [10]. By designing stamping dies of AHS steel sheets springback compensation could be effectively done using the FE simulations [11]. Springback of HSS sheets in U-bending was reduced by applying a counter punch to the die set [12]. The springback effect in bending of AHS steel sheets was reduced by controlling the reduction in thickness of formed part [13]. Additionally, effects of forming speed and holding time at the die bottom were studied. The springback in hat-shaped bending of AHS steel sheets could be eliminated by performing the double-action bending in Ref. [14].

In the present study, a V-shape stamping process of AHS steel sheets grade 980 was investigated. Both experiments and FE simulations of the specified forming procedure were carried out. The Y-U kinematic hardening model was considered, in which uniaxial tensile test and cyclic tension-compression test were performed for determining the appropriate material model parameters. Hereby, FE simulations of 1-element model were conducted in order to verify the calculated cyclic stress-strain curves with the experimental result. Finally, in the simulations, the die clearance at the corner of stamped parts were varied and their effect on occurred springback angles were then evaluated.

2. Experiments

2.1 Material and tensile properties

The steel investigated in this study was the AHS steel sheets grade 980 with an initial thickness of 1 mm. Uniaxial tensile tests under different directions were carried out for characterizing the anisotropic plastic behavior of the investigated steel. The specimens according to DIN EN 10002 standard with a gauge length of 50 mm were prepared. The tensile properties of the steel in varying orientations with regard to the rolling direction were determined, as provided in Table 1. $E$ is the young’s modulus, $YS$ is the yield strength, UTS is the ultimate tensile strength.

| Direction | $E$ (GPa) | YS (0.2% Offset) (MPa) | UTS (MPa) | % Elongation | $r$-Value |
|-----------|-----------|------------------------|-----------|--------------|----------|
| 00°       | 209.87    | 745.47                 | 1013.21   | 7.64         | 13.99    | 1.32       |
| 45°       | 206.35    | 732.82                 | 1014.75   | 7.71         | 15.13    | 1.22       |
| 90°       | 204.69    | 709.96                 | 1016.43   | 7.56         | 14.94    | 1.29       |
| Average   | 206.97    | 729.42                 | 1014.80   | 7.67         | 14.69    | 1.28       |
2.2 Cyclic tension-compression tests

The cyclic tension-compression tests of the investigated steel sheets were conducted up to the total tensile and compressive strains of about 0.10 so that the saturation state of the determined re-loading stress-strain response was achieved. Here, a special test fixture was designed and used in order to prevent a buckling of test sheet samples, as reported in Ref. [10]. A Zeplon spray was applied to reduce friction between clamping plates and specimen. Local displacements of test samples were measured by a digital image correlation (DIC) system. In this work, the pre-strain level of 10 percent was kept. The true stress-true strain curve gathered from the cyclic tension-compression tests was used to identify the material parameters of the Y-U model.

3. Material models

3.1 The Yoshida-Uemori (Y-U) kinematic hardening model

The Yoshida-Uemori (Y-U) kinematic hardening model [6-9] was used in the FE simulations. This model by using the Mat_125 model [15]. This model described a kinematic hardening term, in which an active yield surface (f) and boundary surface (F) were included. The centre of the yield surface can be displaced due to the defined backstress ($\alpha$). The backstress consisted of two components $\beta$ and $\alpha_*$, which are defined by Eq. 1. $\alpha_*$ is the relative kinematic motion of the yield surface, $\beta$ is the centre of the boundary surface, Y is the size of the yield surface, B is the initial size of the bounding surface, and R is the isotropic hardening of the bounding surface.

$$\alpha_* = \alpha - \beta$$

$$\tilde{\alpha}_* = C \left[ \frac{a}{Y} (\sigma - \alpha) - \alpha_0 \right] \tilde{\varepsilon}_p$$

$$\tilde{\varepsilon}_p = \frac{2}{3} D^p : D^p , \quad \alpha_* = \phi(\alpha) , \quad a = B + R - Y$$

$\tilde{\varepsilon}_p$ is the effective plastic strain rate, $D^p$ is defined as the second constant, and $C_1, C_2$ is a material parameter that controls the rate of the kinematic hardening and constants used to modify R. The change of size and position for the boundary surface is defined as following.

$$\dot{R} = k(R_{sat} - R) \tilde{\varepsilon}_p$$

$$\dot{\beta'} = k(\frac{2}{3} b D^p - \beta' \tilde{\varepsilon}_p)$$

$$\sigma_{bound} = B + R + \beta'$$

The evolution equation for $\dot{R}$ (a part of the current radius of the bounding surface in deviatoric stress space), as is with the saturation type of isotropic hardening rule proposed in the original Yoshida model.

$$\dot{\tilde{\varepsilon}} = m(R_{sat} - R) \tilde{\varepsilon}_p$$

is modified as,
$$R = R_{\text{sat}}[(C1 + \varepsilon_p^0)^{C2} - C1^C2].$$

(8)

Where $\beta'$ and $\dot{\beta}'$ are the deviatoric components of $\beta$ and its objective rate, and $b$ is a material parameter. The material parameters of the Yoshida-Uemori model include the parameter $Y$, $C1$, $C2$, $B$, $k$, $b$ and $R_{\text{sat}}$. Beside these six parameters, an additional parameter $h$ is applied to fit the hardening stagnation with experimental results. Moreover, the decrease of elastic stiffness during plastic deformation was also considered. The Young’s modulus $E$ was thus defined according to the following equation [16].

$$E = E_0 - (E_0 - E_{\text{sat}})[1 - \exp(-\xi \varepsilon_p)].$$

(9)

$E_0$ and $E_{\text{sat}}$ represent the elastic modulus value at initial state and infinitely large pre-strain state of material, respectively. $\xi$ is a material constant and $\varepsilon_p$ is the effective plastic strain. Using the stress-strain curves from the monotonic and cyclic tests, the model parameters of the Yoshida-Uemori model could be determined, as summarized in Table 2. Additionally, the parameters, which described the relationships between elastic modulus and applied plastic strain [10], are given in Table 3.

| $Y$ (MPa) | $B$ (MPa) | $k$ | $b$ (MPa) | $R_{\text{sat}}$ (MPa) | $C_1$ | $C_2$ | $h$ |
|-----------|-----------|-----|-----------|------------------------|-------|-------|-----|
| 729.42    | 914.24    | 14.19 | 34.32     | 288.49                 | 65    | 40    | 0.5 |

**Table 2.** Determined material parameters of the Y-U model for the investigated steel.

| $E_0$ (GPa) | $E_{\text{sat}}$ (GPa) | $\xi$ |
|-------------|------------------------|-------|
| 206.97      | 128.40                 | 14.19 |

**Table 3.** Determined parameters for the relationship between elastic modulus and plastic strain.

### 3.2 V-shape stamping test

The forming tests of the V-shape sample were carried out for the examined steel. The schematic view of tools including dimensions of the V-shape stamping test was demonstrated in Figure 1(a). The symmetrical bending angle of 45° was used. The initial blank size was 40 mm in width, 100 mm in length and thickness of 1 mm. After the experiments, resulted dimensions of stamped parts were determined by means of an optical strain measuring system for evaluating the occurred springback. The springback bend angles $\Theta_1$ and $\Theta_2$, as illustrated in Figure 1(b), were considered here. The springback is the geometric change made to a part at the end of the forming process. The final displacement of the punch was varied so that the clearance at the corner of formed samples could be altered between -10% and 10% of the initial sheet thickness. It was aimed in this work to examine the effect of this clearance, $CI$ is Clearance at the corner of the formed part, as depicted in Figure 1(c), on the amount of occurred springback.

![Figure 1](image1.png)

**Figure 1.** (a) Schematic view of tools for the V-shape forming test, (b) bend angles $\Theta_1$ and $\Theta_2$ for evaluating springback effect and (c) Clearance at the corner of the formed part.
3.3 1-Element test

FE simulation of a single element model under cyclic tension-compression load was performed in LSDYNA. The model was a square plane stress element with a size of 1x1 mm. The left-bottom node was constrained in both x- and y-direction, while the right-bottom node was constrained in the y-direction. The displacement is positive and negative y-direction were applied to the top side of the element. Hereby, the element formulation type 2 (Belytschko-Tsay) with one integration point through thickness was used [10]. The Y-U kinematic hardening model referred to the MAT_125 model in LSDYNA [15] was applied and the Y-U parameters were then calibrated with the experimentally obtained curve.

3.4 FE simulations of V-shape stamping

FE simulations of the V-shape forming test were conducted for the investigated steel. The die, punch, binder, blank sample and boundary conditions were defined in the simulations according to the experimental setup. The sample was meshed by using shell element, while all other components were defined as rigid body. The FE models of the V-shape stamping test are illustrated in Figure 2. The Y-U hardening model was employed along with the determined material parameters in the simulations. As a result, the springback angles of formed parts in Figure 1(a) were predicted by the FE simulations and compared with the measured results.

4. Results and Discussion

Firstly, the cyclic stress-strain curves from the 1-element simulations was compared with the experimental tension-compression curve for calibrating the material model parameters, as depicted in Figure 3. It can be seen that the determined parameters of the yield function and Y-U parameters were acceptable since the experimental and numerical results fairly agreed.
Subsequently, from the simulations of the V-shape stamping test the final dimensions of formed samples after tool removal were gathered. The bend angles obtained from the experiment and FE simulation for the case of die clearance equal to the sheet thickness were compared. The resulted deviations were 2.14% and 3.23% for the angles $\theta_1$ and $\theta_2$, respectively. The errors of both angles predicted by the FE simulations coupled with the Y-U model and determined parameters were small. In addition, both springback bend angles were calculated for the cases of applied die clearances varying between 0.9$t$ and 1.1$t$. Then, the predicted angles were compared with the desired angles of 45° and the corresponding percentages of springback were determined, as shown in Table 4. It is seen that the negative die clearance led to slightly larger magnitudes of springback. On the other hand, the positive die clearance of 10% of sheet thickness exhibited a significant reduction of springback angle of the investigated V-shape sample.

Table 4. Calculated springback of V-shape sample in term of bend angles from FE simulations using different die clearances.

| Die clearance | $\%$ Springback |
|---------------|------------------|
|               | $\theta_1$ | $\theta_2$ |
| -10% (0.9$t$) | 6.36     | 7.31     |
| -5% (0.95$t$) | 5.16     | 7.53     |
| 0% (1$t$)      | 5.93     | 5.78     |
| 5% (1.05$t$)   | 5.89     | 5.93     |
| 10% (1.1$t$)   | 3.62     | 3.98     |

5. Conclusions

In this study, springback effects of the AHS steel sheets grade 980 during the V-shape forming process were investigated. Both experiments and FE simulations coupled with the Y-U kinematic hardening model were performed. The material parameters were firstly identified from the determined cyclic tension-compression curves. They were afterwards calibrated by means of the 1-element FE simulations. It was shown that the Y-U model and obtained parameters could successfully predict the resulted bend angles of the formed sample. Furthermore, the effect of die clearance at the edge of the sample on the springback occurrence was studied. It was found that the negative clearance of 10% of the sheet thickness exhibited a noticeable reduction of springback magnitude of the examined steel.

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References

[1] J. Liao, J.A. Sousa, A.B. Lopes, X. Xue, F. Barlat, A.B. Pereira, Mechanical, microstructural behaviour and modelling of dual phase steels under complex deformation paths, International Journal of Plasticity, 93 (2017) 269-290.
[2] W. Gan, R.H. Wagener, Die design method for sheet springback, International Journal of Mechanical Sciences, 46 (2004) 1097-113.
[3] F. Yoshida, H. Hamasaki, T. Uemori, Modelling of anisotropic hardening of sheet metals including description of the Bauschinger effect, International Journal of Plasticity, 75 (2015) 170-188.
[4] S. Sumikawa, A. Ishiwatari, J. Hiramoto, T. Urabe, Improvement of springback prediction accuracy using material model considering elastoplastic anisotropy and Bauschinger effects, Journal of Materials Processing Technology, 230 (2016) 1-7.
[5] R.H. Wagoner, H. Lim, M. Lee, Advanced issues in springback, International Journal of Plasticity, 45 (2013) 3-20.
[6] F. Yoshida, T. Uemori, A model of large-strain cyclic plasticity describing the Bauschinger effect and work hardening stagnation, International Journal of Plasticity, 18 (2002) 661-686.
[7] F. Yoshida, T. Uemori, A model of large-strain cyclic plasticity and its application to springback simulation, International Journal of Mechanical Sciences, 45 (2003) 1687-1702.
[8] B. Chongthairungruang, V. Uthaisangsuk, S. Suranuntechai, S. Jirathearanat, Springback prediction in sheet metal forming of high strength steels, Materials and Design, 50 (2013) 253-266.
[9] H.U. Hassan, H. Traphoner, A. Guner, A.E. Tekkaya, Accurate springback prediction in deep drawing using pre-strain based multiple cyclic stress-strain curves in finite element simulation, International Journal of Mechanical Sciences, 110 (2016) 229-241.
[10] W. Julsri, S. Suranuntechai, V. Uthaisangsuk, Study of springback effect of AHS steels using a microstructure based modelling, International Journal of Mechanical Sciences, 135 (2018) 499-516.
[11] Z. Wang, Q. Hu, J. Yan, J. Chen, Springback prediction and compensation for the third generation of UHSS stamping based on a new kinematic hardening model and inertia relief approach, International Journal of Advanced Manufacturing Technology, 90 (2017) 875-885.
[12] K. Lawanwong, H. Hamasaki, R. Hino, F. Yoshida, Elimination of springback of high-strength steel sheet by using additional bending with counter punch, Journal of Material Processing Technology, 229 (2016) 199-206.
[13] K. Mori, K. Akita, Y. Abe, Springback behaviour in bending of ultra-high-strength steel sheets using CNC servo press, International Journal of Machine Tools and Manufacture, 47-2 (2007) 321-325.
[14] K. Lawanwong, H. Hamasaki, R. Hino, F. Yoshida, Double-action bending for eliminating springback in hat-shaped bending of advanced high-strength steel sheet, The International Journal of Advanced Manufacturing Technology, 106 (2020) 1855-1867.
[15] LS-DYNA, Keyword User’s Manual Version 971 Vol.2: Material Models, Livermore Software Technology Corporation, California, USA, 2007.
[16] W. Prager, A new method of analyzing stresses and strains in work-hardening plastic solids, Journal of Applied Mechanics, 23 (1956) 493-496.