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To cite this article: M. Grubenmann et al 2018 IOP Conf. Ser.: Mater. Sci. Eng. 418 012108

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Analysis of yield locus description on springback behaviour of CR700Y980T-DP steel

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Abstract. To precisely predict springback, the stress and strain state has to be described correctly during the forming process and after load removal. In this work, different yield locus descriptions are considered for springback prediction of a CR700Y980T-DP steel with a thickness of 1.5 mm. Experiments and Finite Element Analyses (FEA) with LS-DYNA of a U-bending validation tool were performed and springback predictions compared. In the FEA Hill48, Barlat89 and Barlat’s YLD2000 for isotropic hardening, Yoshida-Uemori as a kinematic hardening model and the homogeneous anisotropic hardening (HAH) model are chosen. Monotonic and two-step tensile tests with a directional change of stress are performed and cyclic tension-compression tests are used to determine the material parameters of the investigated hardening models. It is seen that both Yoshida-Uemori and HAH models provide a significant improvement in the springback prediction. The results, however greatly depend on the identification procedure as well as on the modelling of cross-loading contraction effects.

1. Introduction
The focus on reduction of CO2 emissions in the automotive industry has led to an increased usage of new steel alloys with high strength such as various advanced high strength steels. Due to their advantageous strength-to-weight ratio, car-body parts with lower sheet thickness can be produced, significant costs can be saved and energy consumption and CO2 emissions are reduced. Nevertheless, the usage of such steels leads to formability problems. The springback behaviour in a formed part has significant influence on the design of tools and hence is sensitive to material and process parameters. This phenomenon occurs mainly due to elastic deformation which appears after removal of the tools. AHSS are more sensitive to springback since they have a higher ratio of flow stress to Young’s modulus. The influence of numerical process parameters add further challenge to this important research topic \cite{1}.

Influence factors for springback behaviour in numerical simulations are e.g. yield stress, work hardening rate, degradation of elastic modulus with increasing plastic strain and friction model during forming \cite{2, 3, 4}. This study focuses on the influence of the yield criterion as it has been emphasized as an important factor for the amount of springback \cite{5}. This aspect has to be understood well to model the material behavior correctly. During the multi-stage stamping processes of automotive parts, the material undergoes complex strain-path changes like tension to compression and vice versa during several cycles of loading and unloading. Classical constitutive models are not able to model these...
changing stress and strain states correctly. Consequently, advanced anisotropic hardening models are needed to cover the associated phenomena namely the Bauschinger effect (BE), latent hardening or contraction and permanent softening [6, 7]. The so-called backstress is a tensorial variable which is used by most of the kinematic hardening models to describe the BE. Progressive deformation leads to a translation of the yield surface’s center in the stress state and therefore to a lower reyielding stress after load reversal. The first kinematic hardening models with a linear hardening response to describe the BE were suggested by Prager [8] and Ziegler [9]. Chaboche and Rousselier considered a nonlinear kinematic-hardening model by superposing a kinematic hardening rule with a nonlinear isotropic one [10]. This approach was extended and improved by several authors. Worth mentioning is the work of Yoshida and Uemori which extended Chaboche’s model with workhardening stagnation and early reyielding based on a mixed isotropic kinematic hardening approach in which the yield surface evolves within a bounding surface with progressing deformation [11]. As an alternative to the before discussed hardening models, the homogeneous anisotropic hardening (HAH) model has been proposed which is able to describe latent effects additionally to the BE. This anisotropic hardening model can be combined with any first order homogenous yield function. The basic idea of this approach is the control of the yield locus distortion by state variables. Therefore the yield locus is deformed and does not shift in stress space like in the aforementioned approaches [12]. In this study the HAH and Yoshida Uemori model will be investigated and their performance of springback prediction on a U-shape profile will be compared to classical hardening models.

2. Material characterization

Tensile tests in rolling, diagonal and transversal direction according DIN EN ISO 6892-1 were performed. Additionally bulge tests according DIN EN ISO 16808 were conducted to compare the hardening behaviour at higher strains. The biaxial stress curve is transformed to the uniaxial case using the principle of equivalent work. The experimental results are shown in Figure 1.

![Figure 1](image_url)

Figure 1. Experimental flow curves with monotonic loading and Hockett-Sherby approximation (left), two stage tensile tests with cross loading path (middle) and cyclic tension-compression tests (right).

To investigate the behaviour under non-proportional hardening behaviour, two stage tensile tests with a directional change of load after a prestrain of 2.5 % are performed. As the transition in this region is gradual, Young’s modulus with an off-set of 0.2 % is used to determine the yielding point. It can be seen that the prestrained material reyields at a higher stress level and converges to the monotonic loading curve with increasing strain. To fit the anisotropic material models, cyclic tension-compression tests are performed. Three prestrain levels are chosen: 2.5 %, 4.0 % and 5.0 % which can be seen in Figure 1 as well.
The obtained mechanical parameters of the material tests are listed in Table 1. These values are the basis for the determination of all hardening models.

<table>
<thead>
<tr>
<th>Angle [°]</th>
<th>$E_0$ [MPa]</th>
<th>Yield stress [MPa]</th>
<th>Uniform El. [-]</th>
<th>UTS [MPa]</th>
<th>Total El. [-]</th>
<th>r-value [-]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0°</td>
<td>191</td>
<td>783</td>
<td>0.051</td>
<td>1060</td>
<td>0.095</td>
<td>0.67</td>
</tr>
<tr>
<td>45°</td>
<td>188</td>
<td>760</td>
<td>0.047</td>
<td>1027</td>
<td>0.086</td>
<td>0.96</td>
</tr>
<tr>
<td>90°</td>
<td>201</td>
<td>790</td>
<td>0.044</td>
<td>1076</td>
<td>0.081</td>
<td>0.82</td>
</tr>
<tr>
<td>Biaxial</td>
<td>-</td>
<td>807</td>
<td></td>
<td></td>
<td></td>
<td>0.97</td>
</tr>
</tbody>
</table>

3. Constitutive models

3.1. Yield curve

For the mathematical approximation of the yield curve in rolling direction a Hockett-Sherby formulation was chosen and is given in equation 1. The approximation is shown in Figure 1.

$$\sigma_y = S_{\text{sat}} - (S_{\text{sat}} - S_0) \exp(-m\epsilon^n)$$ (1)

The Hockett-Sherby model is fitted to the given uniaxial tensile curve in rolling direction and its corresponding hardening parameters are listed in Table 2.

<table>
<thead>
<tr>
<th>$S_{\text{sat}}$ [MPa]</th>
<th>$S_0$ [MPa]</th>
<th>$m$ [-]</th>
<th>$n$ [-]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1466.1</td>
<td>783</td>
<td>1.2937</td>
<td>0.3134</td>
</tr>
</tbody>
</table>

3.2. Isotropic hardening models

For the yield locus description three classical formulations according Hill48, Barlat89 and YLD2000 were chosen. In this study solely output parameters for the material models are discussed. For the material model formulation may as well as the identification procedure be referred to [13-15]. The obtained model parameters are shown in Table 3.

<table>
<thead>
<tr>
<th>Model</th>
<th>Model parameter</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hill48</td>
<td>$F = 0.4893$</td>
</tr>
<tr>
<td>Barlat89</td>
<td>$A = 1.1497$</td>
</tr>
<tr>
<td>YLD2000</td>
<td>$\alpha_1 = 0.889$</td>
</tr>
<tr>
<td></td>
<td>$\alpha_5 = 1.006$</td>
</tr>
</tbody>
</table>

3.3. Anisotropic hardening models

The HAH and a modified Yoshida-Uemori model were chosen as representatives of the advanced anisotropic hardening models. The modified Yoshida-Uemori model allows work hardening in large strain deformation regions and earlier saturation as it occurs for AHSS. Three different effects are considered in the HAH model. The cross-loading contraction effect describes different hardening behaviour in dependence of the given strain and stress condition. The BE characterizes the yield stress reduction when the applied load is reversed. This model approaches this effect with a distortion of the yield locus with deformation. The specific model formulations are given in [11, 12]. In this study, for
both models the above described YLD2000 yield locus description is used. The material parameters of the HAH and Yoshida-Uemori model are fitted to cyclic tension and compression tests using the least squares method. After a uniaxial preload of 2.5 %, 4 % and 5 %, the load is reversed. The hereby obtained model parameters are listed in Table 4. In the case of cross-loading of 45 and 90 degrees, model parameters for describing the BE and latent effects are not completely independent as it became apparent in the fitting process.

Table 4. Input parameters for considered anisotropic hardening models.

<table>
<thead>
<tr>
<th>Model</th>
<th>Model parameter</th>
</tr>
</thead>
<tbody>
<tr>
<td>Yoshida-Uemori</td>
<td>( Y = 583.3MPa ) ( C = 231.1 ) ( B = 865.8MPa ) ( R_{sat} = 0 )</td>
</tr>
<tr>
<td></td>
<td>( b = 286.2MPa ) ( k = 32.56 ) ( h = 0.62 )</td>
</tr>
</tbody>
</table>

| evolution of \( \hat{h} \) | \( k = 1.5 \) \( R = 5 \) \( k_R = 15 \) \( k_r = 0.5 \) \( q = 6 \) |
| Bauschinger effect          | \( k_1 = 53 \) \( k_2 = 200 \) \( k_3 = 0.5 \) \( k_4 = 0.8 \) \( k_5 = 0.25 \) |
| Latent effects             | \( L = 1 \) \( k_L = 0 \) \( S = 0.95 \) \( k_S = 75 \) \( k_P = 4 \) |

Figure 2 shows the experimental cyclic tension-compression tests and the two stage tensile tests which are compared with the predictions of the Yoshida-Uemori and the HAH model. It can be seen, that the HAH model deviates in the region of the earlier reyielding of the material after load reversal. The predictions of the Yoshida-Uemori model fit very well the cyclic experimental results. The HAH model is capable of capturing the cross loading effects as it describes them separately in its formulation. On the contrary, the Yoshida-Uemori model is not capable of predicting the cross loading effects correctly. As the BE and latent effects are in general not fully decoupled a trade-off between a precise fit of the cyclic experiments and the cross loading data has to be found.

Figure 2. Experimental tension-compression tests with anisotropic material model fits (left) and cross-loading from 0 to 90 degrees to RD with anisotropic material model fits.
4. FEA validation and Results

Springback behaviour is investigated in forming of a U-shaped profile. The punch has a width of 70 mm and an edge radius of 5.5 mm. Two different dies with a radius of 3.5 mm and 10.0 mm are considered. For both dies a drawing depth of 80 mm can be reached. The finite element analyses are performed using LS-DYNA. To save computational time symmetrical properties of the geometry are used to build a quarter of the real setup. The forming simulation was done using an explicit solver and an implicit solver for springback analysis. Fully integrated quadrilateral shell elements with an edge length of 1 mm and 9 integration points in thickness direction were chosen. Coulomb friction model with a friction coefficient of 0.1 between blank and tools is used to reproduce the experimental conditions.

4.1. Strain distribution

The blanks are etched with regular point patterns at every 2 mm to record the strain field. The change of distance of the neighbouring points is measured after forming and springback with the ARGUS-system to compute the strains. The distribution of the major strain over the entire specimen is shown in Figure 3. The comparison of the experimental and calculated major strain distribution along the transversal section is shown in Figure 4 in which the origin of the coordinate system is defined as the symmetry point of the punch.

Figure 3. Schematic of the U-bend apparatus (left) and specimen with die radius 10.0 mm after springback and chosen cross section after springback (right).

Figure 4. Experimental and calculated major strain distribution along transversal section with die radius of 3.5 mm (left) and 10.0 mm (right).
The first peak in major strain is located at the position of the punch radius. The second and higher strain peak is caused by the die radius. In the evaluation of the test with a die radius of 3.5 mm none of the material models is capable of describing the strain distribution. In the case of a die radius of 10.0 mm all models show reasonable results. All three isotropic hardening models describe the major strain distribution more precisely than the anisotropic models.

4.2. Springback prediction

After the explicit forming simulation, an implicit springback simulation is performed. The forces are released and the residual stresses are relieved. The results after springback are shown in Figure 5. As expected, the models with isotropic hardening (IH) predict the shape of the specimen similarly and do not allow a good prediction, particularly in the case of die radius 3.5 mm. The deviation of strain distribution in Figure 4 may be an explanation for the deviation of springback prediction for all hardening models. The higher bending ratio leads to increased stresses in thickness direction which are not considered in the shell formulation. The HAH model provides little improvement compared to IH models, whereas the Yoshida model delivers a more accurate prediction. These results are best interpreted keeping in mind the identification procedure summarized in Figure 2. The HAH model has been fitted using both cyclic tension-compression (TC) experiments and two-step tension experiments in 0 and 90 degrees. As the load path change of 90 degrees is not uncoupled from BE, the identification has to compromise accuracy in the early re-yielding experienced in the TC experiments to better approximate the latent contraction in the two-step experiments. As the channel drawing process is dominated by cyclic loading with practically no significant cross-loading occurring the Yoshida model performs better.

![Figure 5. Springback prediction of investigated hardening models in case of a die radius of 3.5 mm (left) and 10.0 mm (right).](image)

In order to make a more fair comparison of the models, the HAH model has also been identified only by using the TC tests. As it can be seen in Figure 6 the so identified HAH model captures the early re-yielding of the material much more accurately.
Figure 6. Comparison of HAH model fitted to BE and CL and solely to BE considering Cyclic tension-compression tests and two-stage tensile tests.

The corresponding model parameters are given in Table 5.

**Table 5.** Input parameters for HAH model fit to tension-compression tests.

<table>
<thead>
<tr>
<th>Model</th>
<th>Model parameter</th>
<th>Evolution of $\hat{h}$</th>
<th>Bauschinger effect</th>
<th>Latent effects</th>
</tr>
</thead>
<tbody>
<tr>
<td>HAH</td>
<td>$k = 1.5$</td>
<td>$R = 5$</td>
<td>$k_R = 15$</td>
<td>$L = 1$</td>
</tr>
<tr>
<td></td>
<td>$k_1 = 53$</td>
<td>$k_2 = 200$</td>
<td>$k_3 = 0.5$</td>
<td>$k_L = 0$</td>
</tr>
<tr>
<td></td>
<td>$k_4 = 0.5$</td>
<td></td>
<td>$k_4 = 0.8$</td>
<td>$S = 0.95$</td>
</tr>
<tr>
<td></td>
<td>$k_5 = 0.25$</td>
<td></td>
<td></td>
<td>$k_P = 4$</td>
</tr>
<tr>
<td></td>
<td>$q = 6$</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

This accuracy is also directly reflected to the springback results in Figure 7 where the two considered models deliver comparable results.

Figure 7. Influence of material parameter identification on performance of springback prediction in case of a die radius of 3.5 mm (left) and 10.0 mm (right).
5. Conclusions
In this study a CR700Y980T-DP steel with a thickness of 1.5 mm was tested with monotonic and two-stage tensile tests, Bulge tests and cyclic tension-compression tests to determine the isotropic material models according Hill48, Barlat89 and YLD2000 and the anisotropic material models Yoshida-Uemori and HAH. As it can be expected both anisotropic hardening models enabled a significant improvement in the springback prediction. The HAH model is built modularly and is capable of accounting for the BE and latent effects. Therefore it is important to fit the model to its application as it was shown that the results greatly depend on the identification procedure and the modeling of the cross-loading contraction effects. In the case in which the HAH model was fitted only considering the BE its springback prediction is similar to the Yoshida model and shows better results than fitting the BE and cross-loading effects. However, future work has to be done to apply the HAH and Yoshida model to processes with more complex and nonlinear strain and stress paths to show the influence of the parameter identification procedure.

References