On the role of Anisotropy and Bauschinger-Effect in Sheet Metal Spinning

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Abstract. Incremental sheet forming is known for its local forming character where the material is continuously bent and unbent in a multitude of tool passes. By this nature, anisotropy and Bauschinger-Effect might play a significant role in numerical modelling of the process. This paper aims to assess different material modelling techniques by comparing the resulting stress and strain histories of the FEM simulations. Amongst these are Barlats non-quadratic yield locus Yld2000-2d yield criterion and the homogeneous anisotropic hardening model.

1. Introduction
During the last two decades, incremental sheet forming (ISF) processes have arisen a lot of attention. They are known to have some unique advantages over classical sheet metal forming processes, such as the fact, that strains can be obtained well above the forming limit curve (FLC) ([1]). Figure 1 illustrates the conventional metal spinning process. A circular blank is clamped on a machine which is similar to a lathe. Under high rotational velocities, a roller tool is used to gradually force the blank onto the mandrel in multiple passes.

In the last ten years a multitude of studies has been conducted using finite element method (FEM). [2] investigated different variations in the feed rate, direction and type of the roller tool. [3] simulated a dual pass process and validated against experimental data. [4] investigated material deformation in a 5-pass spinning experiment. Using the same model, [5] studied the effects of different roller path profiles. [6] modelled and validated a 9-pass experiment. They traced and analysed the strain paths during the process in a specified region and recognized that the material underlies cyclic straining. Based on these findings they emphasized the importance of incorporating complex aspects in material modelling, such as Bauschinger-Effect (BE).

In the context of metal spinning, material modelling plays a sensitive role on instabilities such as wrinkle formation. As these strongly depend on the stress history in the component, it is important to correctly map the yield locus and its development. This paper aims to compare the stress and strain history for multi-pass conventional sheet metal spinning simulations using various material modelling techniques. Three different models have been considered: a) von Mises yield criteria with isotropic hardening, b) Barlats non-quadratic yield locus Yld2000-2d yield criterion ([8]) with isotropic hardening and c) Yld2000-2d yield criterion with the homogeneous anisotropic hardening (HAH) model ([9]).
2. Material Characterization

Because this work consists of a purely numerical analysis and the acquisition of material data, especially with load reversal, is bound to complex procedures, data from literature are used. In the dissertation thesis of [10] extensive data for deep drawing quality steel (DC05) has been obtained. The same data is also available in a more compact format in the contribution by [11] and is used for further investigation.

2.1. Flow curves and yield locus

In Figure 2a the stress versus plastic strain curves in 0, 45 and 90 to rolling direction are illustrated. Combined with the E-Modulus and the Poisson’s ratio ($E = 210$ GPa and $\nu = 0.30$) this data can be used to model elasto-plastic material in LS-DYNA.

The flow curves and the data in table 1 deliver all the necessary input quantities to characterize the Yld2000-2d model whose formulation is given as in equation (1)

$$
\Psi = |X'_1 - X'_2|^a + |2X''_2 - X''_1|^a + |2X''_1 - X''_2|^a = \bar{\sigma}^a
$$

where $\bar{\sigma}$ is the equivalent stress, $a$ is the crystal structure exponent of the Face Cubic Center (FCC) material which is considered to be 6 and $X'_1, X'_2, X''_1$ and $X''_2$ are the principal values of two linear transformations of the stress deviator defined as:

$$
X' = C's = C'T\sigma = L'\sigma \quad X'' = C''s = C''T\sigma = L''\sigma
$$
Figure 2: (a) Flow curves in 0, 45 and 90 for DC05 (b) Yld2000-2d yield locus shape for $\epsilon_p = 0.05, 0.10$ and $0.15$.

with

\[
L'_{11} = \frac{2}{3} \alpha_1 \\
L'_{12} = -\frac{1}{3} \alpha_1 \\
L'_{21} = -\frac{1}{3} \alpha_2 \\
L'_{22} = \frac{2}{3} \alpha_2 \\
L'_{33} = \alpha_7 \\
L''_{11} = \frac{-2\alpha_3 + 2\alpha_4 + 8\alpha_5 - 2\alpha_6}{9} \\
L''_{12} = \frac{4\alpha_3 - 4\alpha_4 + 4\alpha_5 + \alpha_6}{9} \\
L''_{21} = -\frac{2\alpha_3 + 8\alpha_4 + 2\alpha_5 - 2\alpha_6}{9} \\
L''_{22} = -\frac{-\alpha_3 - 4\alpha_4 + 4\alpha_5 + 4\alpha_6}{9} \\
L''_{12} = -\frac{\alpha_3 - 4\alpha_4 + 4\alpha_5 + 4\alpha_6}{9}
\]

Figure 2b depicts the resulting Yld2000-2d yield locus for different plastic strains ($\epsilon_p = 0.05, 0.10$ and $0.15$).

Table 1: DC05 mechanical properties and corresponding yield locus parameters for Yld2000-2d Yield Criterion (all stresses in MPa).

| $\sigma_0^y$ | $\sigma_45^y$ | $\sigma_90^y$ | $\sigma_0^b$ | $\sigma_45^b$ | $\sigma_90^b$ | $\rho_0$ | $\rho_45$ | $\rho_90$ | $\rho_b$ |
|-------------|---------------|---------------|--------------|---------------|---------------|---------|---------|---------|---------|
| 171         | 178           | 177           | 195          | 2.00          | 1.47          | 2.52    | 0.85    |         |         |
| $\alpha_1$  | $\alpha_2$    | $\alpha_3$    | $\alpha_4$   | $\alpha_5$    | $\alpha_6$    | $\alpha_7$ | $\alpha_8$ |         |         |
| 1.08        | 0.98          | 0.85          | 0.88         | 0.91          | 0.84          | 0.97    | 0.98    |         |         |

2.2. Bauschinger-Effect

As mentioned in literature ([7]) and shown in section 4.1, the material underlies cyclic straining by bending and partial unbending in each tool pass. This indicates that the BE might play a significant role in the stress development of the component. In this work the HAH model ([9]) is used to investigate the role of BE in conventional metal spinning processes. It is given as in equation 3

\[
\bar{\sigma} = (\phi^a + \phi_h^a)^{1/a}
\]
where $\phi$ is the stable component, which is any homogeneous orthotropic yield locus description. $\phi_h$ is a homogeneous component formulated as follows:

$$
\phi_h = f_1|\xi - |\xi|| + f_2|\xi + |\xi||
$$

where $\xi = \hat{h}^s : s$, $s$ is the deviatoric part of the stress tensor and $\hat{h}^s$ the microstructure deviator defined as:

$$
\hat{h}^s = \frac{h^s}{\sqrt{\frac{2}{3} h^s : h^s}}
$$

At the moment of first plastic deformation $h^s$ is equal to the deviatoric stress tensor. Later it is evolved depending on the equivalent plastic strain. $f_1$ and $f_2$ depend on two state variables $g_1$ and $g_2$ describing the ratio of the distorted deviatoric stress to the isotropic stress:

$$
f_1 = (g_1^{-q} - 1)^{1/q} \quad \quad f_2 = (g_2^{-q} - 1)^{1/q}
$$

In case of no permanent softening [9] suggest the following evolution equations:

$$
\begin{align*}
\frac{dg_1}{d\bar{\epsilon}} &= k_2 \left( k_3 \frac{H_0}{H} - g_1 \right) & \frac{dg_1}{d\bar{\epsilon}} &= k_1 \left( \frac{1 - g_1}{g_1} \right) \\
\frac{dg_2}{d\bar{\epsilon}} &= k_1 \left( 1 - g_2 \right) & \frac{dg_2}{d\bar{\epsilon}} &= k_2 \left( k_3 \frac{H_0}{H} - g_2 \right) \\
\frac{d\hat{h}^s}{d\bar{\epsilon}} &= k \left( \hat{s} - \frac{8}{3} \hat{h}^s \left( \hat{h}^s : \hat{s} \right) \right) & \frac{d\hat{h}^s}{d\bar{\epsilon}} &= -k \left( \hat{s} - \frac{8}{3} \hat{h}^s \left( \hat{h}^s : \hat{s} \right) \right)
\end{align*}
$$

where $k_i$ are the model parameters which have been identified by conducting cyclic shear tests. Figure 3 shows the curves derived from the experiments, as well as the approximation obtained with the HAH model. It can be seen, that the model captures both, early re-yielding and increased hardening rate quite well. The HAH model parameters are listed in table 2.

![Figure 3: Reverse shear experiments and HAH fit](image)

where $\hat{s}$ is the stable component, which is any homogeneous orthotropic yield locus description. $\phi_h$ is a homogeneous component formulated as follows:

$$
\phi_h = f_1|\xi - |\xi|| + f_2|\xi + |\xi||
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where $\xi = \hat{h}^s : s$, $s$ is the deviatoric part of the stress tensor and $\hat{h}^s$ the microstructure deviator defined as:

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\frac{dg_2}{d\bar{\epsilon}} &= k_1 \left( 1 - g_2 \right) & \frac{dg_2}{d\bar{\epsilon}} &= k_2 \left( k_3 \frac{H_0}{H} - g_2 \right) \\
\frac{d\hat{h}^s}{d\bar{\epsilon}} &= k \left( \hat{s} - \frac{8}{3} \hat{h}^s \left( \hat{h}^s : \hat{s} \right) \right) & \frac{d\hat{h}^s}{d\bar{\epsilon}} &= -k \left( \hat{s} - \frac{8}{3} \hat{h}^s \left( \hat{h}^s : \hat{s} \right) \right)
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$$

where $k_i$ are the model parameters which have been identified by conducting cyclic shear tests. Figure 3 shows the curves derived from the experiments, as well as the approximation obtained with the HAH model. It can be seen, that the model captures both, early re-yielding and increased hardening rate quite well. The HAH model parameters are listed in table 2.
3. Process modeling
In this section the 3D FEM Model of the process is delineated. The simulations are conducted using the commercial FEM code LS-DYNA. Figure 4a displays the model setup of the process. Involved components are: mandrel (red), toller tool (blue), tailstock (yellow) and circular blank (green).

![Figure 4](image)

Table 2: HAH model parameters ([11])

| $k$ | $k_1$ | $k_2$ | $k_3$ | $k_4$ | $k_5$ |
|-----|-------|-------|-------|-------|-------|
| 28  | 158.4 | 6.3   | 0.1   | 0.9   | 10    |

All components are meshed using quadrilateral shell elements. The tools are modeled as undeformable rigid structures. For the blank a selectively reduced (S/R) integrated shell element formulation with five integration points in thickness direction is applied. This is a very efficient element formulation that enables the application of the Yld2000-2d Yield Criterion and the HAH model. Its downside is the negligence of through thickness stress, however [7] have shown that the results agree with experimental data very well, as far as thickness and geometry concerns. Figure 4b shows a sensible strategy for meshing the blank. In the flange area, a very fine mesh is applied (80 x 240 elements). As there is only very little deformation in the center area where the blank is clamped, the mesh is neglected for efficiency purposes.

The incremental forming character with complex contact conditions and high non-linearity in metal forming demands the application of explicit solvers with very small time steps. Because conventional metal spinning processes are bound to large production times, disproportionately high computational times are generated. To reduce the overall process time, the process velocity can be increased. As metal spinning is a dynamic process, this might significantly influence the system response, therefore no time scaling is applied in this work. To accelerate result calculation, the critical time step can be increased by selective mass scaling (SMS). Unlike conventional mass scaling, SMS does not lead to unwanted mass increase of the system.

The basic material modelling (i.e. von Mises yield criteria with isotropic hardening) with an elasto-plastic material is based on the stress versus plastic strain curve for different strain rates provided in section 2. To account for the anisotropic characteristics of the material using Barlats nonquadratic yield criterion Yld2000-2d, LS-DYNA offers a predefined internal function. The $\alpha$-parameters provided in table 1 and the crystal structure exponent are used for configuration of the yield locus. For the HAH model in combination with Yld2000-2d the same code as in [11] has been used. The $k$-parameters listed in table 2 characterize the homogeneous anisotropic hardening behaviour.
4. Influence of Anisotropy and Bauschinger-Effect

The FEM model introduced in the previous section delivers a good approximation for multi-stage conventional metal spinning processes. The next question is whether the advanced material models entail a relevant difference to each other. Figure 5a shows the final geometry of the workpiece and the tool path of the roller tool which consists of 9 stages. Figure 5b illustrates the roller tool geometry with a nose radius of 23 mm and attack angle of 35 degrees.

![Figure 5: (a) Tool path and final geometry of the workpiece (b) Duraspin R23 roller tool (7)](image)

To compare the results of the different material modelling approaches, an element in the flange area is selected which is passed during each of the first six stages ($t = 0-14.5$ s). In the following two subsections the stress and strain history of the specified element are analysed.

4.1. Strain analysis

As mentioned in section 2.2 in each tool pass the material undergoes a bending and partial unbending operation. This indicates that the highest strain amplitudes are observed in the border layers. Therefore the radial and circumferential strains ($\epsilon_{rr}$ and $\epsilon_{\theta\theta}$) are plotted for the top layer in figures 6a and 6b. The element orientation is specified in figure 4b.

The green dashed line in figure 6a and 6b represents the strain history in the model with the von Mises yield criteria with isotropic hardening. As the blank is gradually forced on the mandrel the material is stretched in radial direction ($\epsilon_{rr} > 0$) and compressed in circumferential direction ($\epsilon_{\theta\theta} < 0$). Stages 4, 5 and 6 in figure 6a emphasize the bending and partial unbending nature of the process in radial direction. This characteristic is barely visible in circumferential direction.

For the first tool pass the models yield very similar results. In the subsequent stages significant deviations in the strain history are observable, especially for the HAH model. It is self-evident that these deviations are also detectable in the stress history which is discussed in the following section.

4.2. Stress analysis

Metal spinning is a dynamic process where the stress response is expected to be fluctuating. To make a meaningful comparison, the unfiltered local element stresses in the top layer are
analysed in a relative small time window which encloses the element history of stage number 6 ($t = 12.7 - 14.5 \, s$).

The blue solid line in figure 7a shows the development of the radial stress ($\sigma_{rr}$) using von Mises yield criteria with isotropic hardening. In each revolution ($\Delta t = 0.05 \, s$) the specified element is loaded with a strain increment which leads to a peak in the stress pattern. These peaks are crucial for the forming process and can be connected to form an envelope which is named stress amplitude (red dashed line). The stress amplitude shows a clear trend. At first, during the bending operation, the top element layer undergoes tensile strains leading to positive stresses. During the following partial unbending operation the element is compressed, yielding negative stresses. Similar observations are made for the simulations using Yld2000-2d yield criterion with isotropic hardening (Fig. 7b) and Yld2000-2d with HAH (Fig. 7c). Figure 7d shows an overall comparison of the stress amplitudes. It can be seen that during the bending operation all models yield a similar value for the maximum of the stress amplitude. However during the unbending operation, the stress amplitude is greatly overestimated for the models which do not incorporate BE. This behaviour is related to the early re-yielding during load reversal. The element enters the plastic domain at an earlier point resulting in smaller absolute values of the stress amplitude.

Figure 6: (a) Radial strain ($\epsilon_{rr}$) history in top layer (b) Circumferential strain ($\epsilon_{\theta\theta}$) history in top layer
5. Conclusion

This paper compares different material modelling techniques for conventional sheet metal spinning processes. These models involve basic material modelling with a) von Mises yield criteria and isotropic hardening but also more sophisticated approaches like b) Yld2000-2d yield criteria with isotropic hardening and c) Yld2000-2d yield criteria with HAH. The presented models are tested on a multi-pass experiment and show deviations in the stress and strain history, especially for the HAH model.

- Models a and b yield similar results in terms of stress and strain development
- Compared to models a and b, model c shows significant differences in stress and strain history
- Model c captures the early re-yielding during load reversal which leads to a different stress pattern

In sheet metal spinning the stress development plays a great role for modelling instabilities such as wrinkle formation. Therefore it is important to incorporate BE because, as it has been shown in this work, it has a significant influence on the element history and thereby can play a key role in failure detection.
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