Accurate hardening modeling as basis for the realistic simulation of sheet forming processes with complex strain-path changes

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Summary:

Sheet metal forming involves large strains and severe strain path changes. Large plastic strains lead in many metals to the development of persistent dislocation structures resulting in strong flow anisotropy. This induced anisotropic behavior manifests itself in the case of a strain path change by very different stress-strain responses depending on the type of the strain path change. While many metals exhibit a drop of the yield stress (Bauschinger effect) after a load reversal, some metals show an increase of the yield stress after an orthogonal strain path change (so-called cross hardening). To model the Bauschinger effect, kinematic hardening has been successfully used for years. However, the usage of the kinematic hardening leads automatically to a drop of the yield stress after an orthogonal strain path change contradicting experimental results for materials exhibiting the cross hardening effect. Another effect, not accounted for in the classical elasto-plasticity, is the difference between the tensile and compressive strength, exhibited e.g. by some steel materials. In this work we present a phenomenological material model whose structure is motivated by polycrystalline modeling that takes into account the evolution of polarized dislocation structures on the grain level – the main cause of the induced flow anisotropy on the macroscopic level. The model considers besides the movement of the yield surface and its proportional expansion, as it is the case in conventional plasticity, also the changes of the yield surface shape (distortional hardening) and accounts for the pressure dependence of the flow stress. All these additional attributes turn out to be essential to model the stress-strain response of high-strength steels subjected to non-proportional loading. The model is implemented into LS-DYNA via the user material interface. After a LS-OPT based parameter identification for a dual phase high strength steel with the help of one- and two-stage loading tests, we demonstrate the capability of the model to predict the spring-back in processes with complex strain path changes.

Keywords:
Induced flow anisotropy, distortional hardening, cross hardening, strain-path changes, pressure dependent plasticity, sheet forming.

1 Introduction

Metal forming processes involve large plastic strains and severe strain path changes. Large plastic strains lead in many metals to strong flow anisotropy. This induced anisotropic behavior manifests itself in the case of a strain path change by very different stress-strain responses depending on the type of the strain path change [1]. To describe two-stage strain path changes, Schmitt et al. introduced in [2] the scalar parameter

$$\theta = \boldsymbol{N}_1 \cdot \boldsymbol{N}_2 \tag{1}$$

Here, $\boldsymbol{N}_1$ and $\boldsymbol{N}_2$ are the strain-rate direction before and after the strain-path change, respectively. For example, if θ equals -1, one speaks about a load reversal, and if θ is 0, the strain-path change is referred to as orthogonal.

While many metals exhibit a drop of the yield stress (Bauschinger effect) after a load reversal, some metals show an increase of the yield stress after an orthogonal strain path change (so-called cross hardening effect). The reason for this induced flow anisotropy is the development of persistent dislocation structures during large deformations [3]. These consist of walls of high dislocation density separating low dislocation density areas. The one side of each wall contains excess dislocations of the same sign, and the other side such dislocations of the opposite sign. After a load reversal, plastic deformation takes place due to the slip on the same slip systems but in opposite direction. Excess dislocations, since they repel each other, facilitate this slip, resulting in the Bauschinger effect. After an orthogonal strain path change, new slip systems are activated and the existing dislocation walls act as obstacles, resulting in the cross hardening effect.

To model the Bauschinger effect, the concept of kinematic hardening has been successfully used for years. However, the presence of kinematic hardening results in a drop of the yield stress after an orthogonal strain path change, which contradicts tests results on materials exhibiting the cross hardening effect. Accordingly, the combined isotropic-kinematic hardening ansatz is insufficient to describe the constitutive behavior of materials, exhibiting both the Bauschinger and the cross hardening effects, and has to be extended. Another effect, not accounted for in the classical elasto-plasticity, is the difference between the tensile and compressive strength (strength differential effect), exhibited e.g. by some steel materials [4].

In this work we analyze the mechanical response of a dual phase high strength sheet steel in one- and two-stage loading processes. It turns out that the material exhibits the strength differential effect and that the deformation induced flow anisotropy is to complex to be modeled by the combined hardening ansatz. To describe the constitutive response of the investigated material, we extend the isotropic-kinematic-distortional hardening model, presented at the ESAFORM 2006 [5], by incorporating the first invariant of the stress tensor into the yield condition. The model is implemented into LS-DYNA via the user material interface. After a LS-OPT based parameter identification for a dual phase high strength steel with the help of one- and two-stage loading tests, we demonstrate the capability of the model to predict the spring-back in processes with complex strain path changes.

2 Model for pressure dependent directional hardening

In [5] we presented a macroscopic material model whose structure is motivated by polycrystalline modeling [6] that takes into account the evolution of polarized dislocation structures at the grain level representing the main cause of the induced flow anisotropy on the macroscopic level. Besides a shift of the yield surface and its proportional expansion as in the case of conventional plasticity, the presented model also accounts for the changes of the yield surface shape (distortional hardening). To be able to describe the pressure dependent yielding behavior, exhibited e.g. by some steel materials, we incorporate the trace of the stress tensor into the yield function [4]

$$\phi = \sigma_e + a\,tr(\boldsymbol{T}) - Y \tag{2}$$

where Y is the yield stress, whose evolution is determined by Voce isotropic hardening, a is a material parameter, governing the yield stress pressure sensitivity, and

$$\sigma_e = \sqrt{\boldsymbol{\Sigma} \cdot (\boldsymbol{M}_{Hill} + \boldsymbol{H})\boldsymbol{\Sigma}} \tag{3}$$

represents the equivalent stress measure. Here,

$$\boldsymbol{\Sigma} := \boldsymbol{T}' - \boldsymbol{X} \tag{4}$$

is the difference between the deviatoric part of the Cauchy stress $\boldsymbol{T}$ and the back stress $\boldsymbol{X}$, $\boldsymbol{M}_{Hill}$ is the orthotropic fourth-order Hill tensor, describing the initial flow anisotropy due to texture, and $\boldsymbol{H}$ the fourth-order tensor, introduced to represent distortion of the yield surface due to dislocation structures. The plastic strain rate is given by the associative flow rule

$$\boldsymbol{D}_p = \dot{\lambda} \frac{\partial \phi}{\partial \boldsymbol{T}'} \ . \tag{5}$$

Note, that taking the derivative of the yield function with respect to the deviatoric stress part insures the plastic incompressibility of the material, which is a good approximation even for steel materials exhibiting the strength differential effect [4].

Ignoring any texture effects for simplicity, the Jaumann rate of the Cauchy stress is given by the isotropic hypo-elastic relation

$$\overset{\circ}{\boldsymbol{T}} = 2\mu\left(\boldsymbol{D} - \boldsymbol{D}_p\right) + \lambda tr\left(\boldsymbol{D} - \boldsymbol{D}_p\right)\boldsymbol{I} \ . \tag{6}$$

Further, the evolution of the kinematic hardening is given by the Armstrong-Frederick relation

$$\overset{\circ}{\boldsymbol{X}} = C_X\left(X_{Sat}\boldsymbol{D}_p - \boldsymbol{X}\dot{\lambda}\right) . \tag{7}$$

The fourth-order tensor $\boldsymbol{H}$, representing distortional hardening, is described by the following evolution equation

$$\overset{\circ}{\boldsymbol{H}} = C_D(D_{Sat} - H_D)(\boldsymbol{N} \otimes \boldsymbol{N})\dot{\lambda} + C_L[L_{Sat}(\boldsymbol{I}_{dev} - \boldsymbol{N} \otimes \boldsymbol{N}) - \boldsymbol{H}_{\boldsymbol{L}}]\dot{\lambda} \tag{8}$$

Here, $\boldsymbol{I}_{dev}$ is the deviatoric part of the fourth-order identity tensor, $\boldsymbol{N}$ the direction of the plastic strain-rate, H_D the projection of $\boldsymbol{H}$ onto the direction of the plastic strain-rate

$$H_D = \boldsymbol{H} \cdot (\boldsymbol{N} \otimes \boldsymbol{N}) \ . \tag{9}$$

Further, $\boldsymbol{H}_L$ is the part of $\boldsymbol{H}$ orthogonal to $\boldsymbol{N}$

$$\boldsymbol{H}_{\boldsymbol{L}} = \boldsymbol{H} - H_D(\boldsymbol{N} \otimes \boldsymbol{N}) \ . \tag{10}$$

In addition, D_{Sat} and C_D represent the saturation value and saturation rate parameters, respectively, for H_D, while L_{Sat} and C_L, respectively, represent these parameters for the latent part $\boldsymbol{H}_L$.

To understand the behavior of the current model, we consider an initially annealed material state with vanishing $\boldsymbol{H}$ and assume $L_{Sat} < 0$ as well as for simplicity $D_{Sat} = 0$. If the material is subjected to proportional loading in the direction $\boldsymbol{N}_1$, the directional part H_D does not evolve since $D_{Sat} = 0$. Consequently, only $\boldsymbol{H}_L$ evolves, saturating to the value $L_{Sat}(\boldsymbol{I}_{dev} - \boldsymbol{N}_1 \otimes \boldsymbol{N}_1)$, which is orthogonal to $\boldsymbol{N}_1$. Such an evolution of $\boldsymbol{H}$ does not influence the yield strength of the material in the loading direction $\boldsymbol{N}_1$, while the strength in all directions, being orthogonal to that of the loading direction, increases. After an orthogonal strain-path change with re-loading direction $\boldsymbol{N}_2$, the directional part as the projection of $\boldsymbol{H}$ onto $\boldsymbol{N}_2$ takes on a negative value and saturates toward zero during re-loading due to $D_{Sat} = 0$. This results in shrinkage of the yield surface in the direction of re-loading. On the other hand, the yield surface expands in direction $\boldsymbol{N}_1$ since $\boldsymbol{N}_1$ is now orthogonal to the current loading direction. This behavior corresponds qualitatively to that obtained by Peeters et al. in [6], using a microstructural model that accounts on the grain level for the evolution of polarized dislocation sheets.

With the presented model it is possible to describe both the Bauschinger and the cross hardening effects, simultaneously. The model was implemented as a user-defined material in LS-DYNA 971.

3 Model identification

To demonstrate the suitability of the presented model to describe the complex pressure dependent hardening behavior under non-proportional loading, we use it to simulate the constitutive behavior of a dual phase high strength sheet steel. (Due to commercial dependency, the experimental results can be given only in scaled format.)

Figure 1 left shows clearly that the investigated material exhibits the difference between the tensile and compressive yield strength. Similar behavior was reported in [4] for bulk high strength steels. Tension and compression experiments in rolling (RD) and transverse (TD) directions after 10% tensile pre-strain in RD (Fig. 1 right) shows that the material exhibits both the Bauschinger and the cross hardening effect. Accordingly, such a behavior cannot be described by classical pressure independent combined hardening models.

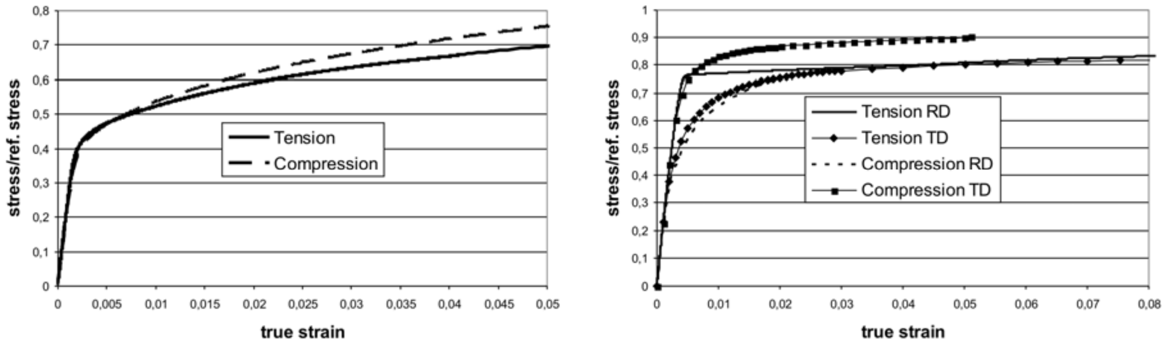

Fig. 1: Experimental results. Left: tensile and compressive yield curves in RD on the as-received material. Right: tensile and compressive yield curves after 10% tensile pre-strain in RD.

In contrast, applying the model, described in the previous section, it was possible to determine the material parameters in such a way that the whole set of experimental data can be described with a good accuracy (Fig. 2). The parameter optimization was carried out with the help of the program LS-OPT in combination with LS-DYNA as based on one solid element simulations.

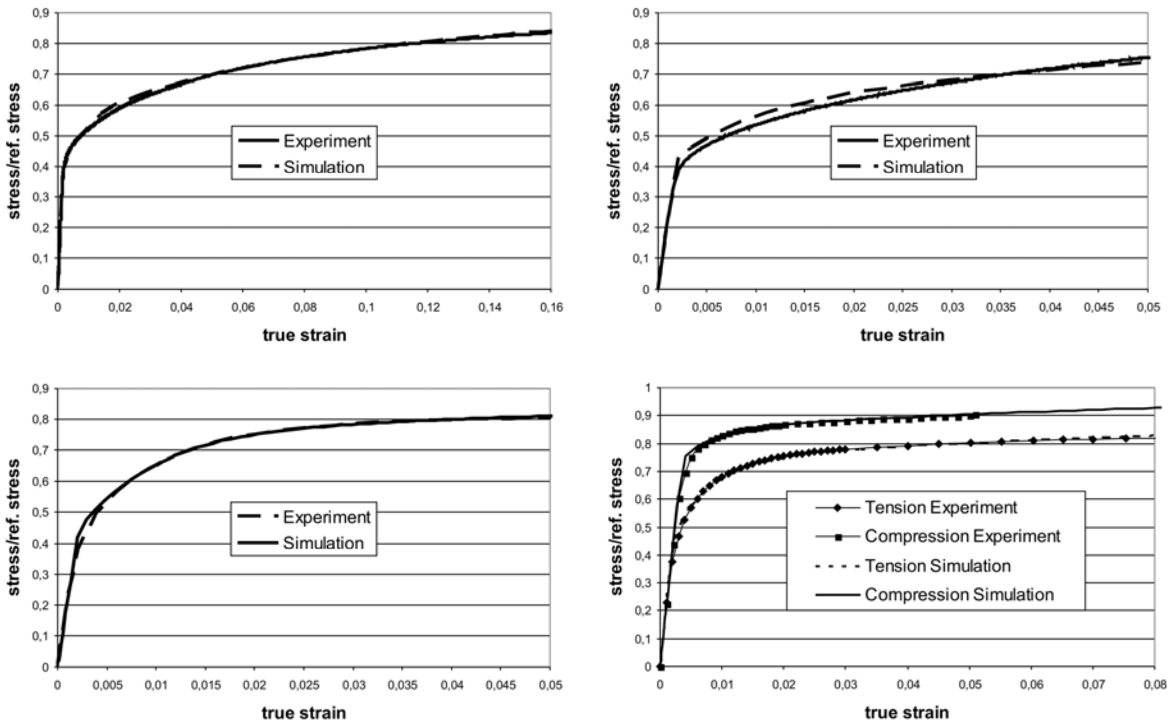

Fig. 2: Comparison of experimental and numerical results. Upper left: uniaxial tension in RD. Upper right: uniaxial compression in RD. Lower left: uniaxial compression in RD after 10% tensile pre-strain in RD. Lower right: uniaxial tension and compression in TD, respectively, after 10% tensile pre-strain in RD.

On the basis of simulations results, shown in Fig. 2, the mixture of isotropic, kinematic and distortional hardening in combination with the yield function, depending on the trace of the stress tensor, seems to be an adequate constitutive ansatz to model the directional pressure dependent hardening behavior of dual phase high strength steels. (Due to commercial dependency, it is not possible to give the material parameters.)

4 Model application

An accurate modeling of the deformation induced flow anisotropy is crucial for the spring back simulation in processes with complex strain path changes. As an application example for a structural spring back simulation we consider first the strip drawing test proposed as a spring back benchmark test at the NUMISHEET'93 conference. Fig. 3 shows experimental and numerical results for the released strips have being drawn under the following process characteristics: the ratios of the sheet thickness to the punch radius and to the die radius were 0.2 and 0.14, respectively. The application of the proposed model yields a good agreement with the experiment. Similarly good agreements were also reported in different works where only the combined hardening was used.

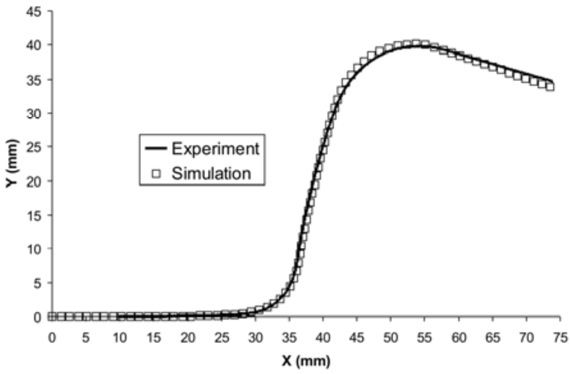

Fig.3: Comparison of experimental and numerical results: released sheet strips after drawing (the half of the geometry is displaced).

As an example for structural simulations with more complex strain path changes then the load reversal as in the case of strip drawing we consider the deep-drawing process of a cylindrical cup. The fact that material points are subjected predominantly to tangential compression as long as they are in the flange area, followed by either radial tension for the inward cup side or radial compression for the outward cup side during the bending stage, results in complex strain path changes in the sheet. Due to the closed shape and accordingly high structural stiffness, the drawn cup contains high residual stresses, which are strongly dependent on the material hardening behavior. To estimate these stresses, the so-called ring splitting test [7] represents a very effective way. In the ring splitting test several rings are cut out of the frame of a cylindrical deep-drawn cup and then split as shown in Fig. 4.

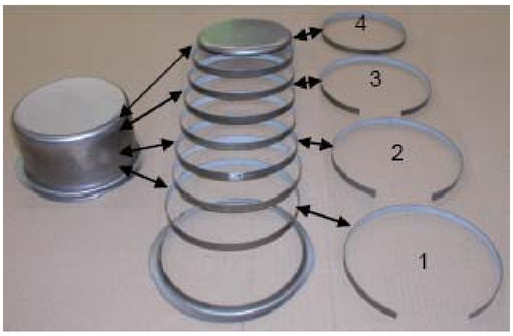

Fig.4: Ring splitting test on DC04 from [7].

To reveal the dependency of the residual stresses on the material hardening behavior, we simulated the ring splitting process (Fig. 5), applying the proposed model with parameters as used in Fig. 2 and the combined hardening model with material parameters fitted to the monotonic tensile test and to the tensile test with load reversal. For the rings 1 and 3, the current material model yields an excellent agreement with experimental results while the opening of the ring 2 is underestimated (Table 1). On the other hand, the openings of all rings simulated with the combined hardening model are approx. 30 mm smaller then obtained with the current model, which is approximately 35% of the punch diameter. The difference in the numerical ring openings results, undoubtedly, from the difference in the residual stresses obtained using different hardening models. Due to the additional hardening mechanism (distortional hardening) the current model behaves apparently harder in processes with complex strain-path changes. Accordingly, this example demonstrates what influence the hardening behavior can have on residual stresses in sheet forming processes with complex strain-path changes.

Fig.5: Ring splitting simulation. Left: the current model, right: combined hardening ansatz.

openings (mm)	complete model	combined	experiment
ring 1	270	242	270
ring 2	316	277	346
ring 3	320	292	317

Table 1: Results for experimental and numerical ring openings simulated with the complete and combined hardening models.

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6 Literature

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