

Analysis of the stress and directional dependent Bauschinger-effect of sheet metals

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Abstract. The increasing application of lightweight metals in combination with a growth in the complexity of components provides new challenges to the numerical modeling of sheet materials. The choice of the material model and the associated mapping of the hardening behavior are of substantial importance for a realistic process prediction and the following spring back calculation in particular. The implementation of the Bauschinger-effect via isotropic-kinematic hardening laws can lead to a substantial improvement of the prediction quality. It is commonly known, that an accurate prognosis of sheet metal forming processes requires the consideration of the semi-finished products anisotropy. However, the identification of the Bauschinger-effect, which describes the reduction of the yield stress after a load reversal, and corresponding numerical models, is usually done under a specific stress state and in one direction of the sheet. Considering the vast variety of stress states and loading directions occurring in a forming operation, the anisotropic behavior of the Bauschinger-effect under uniaxial stress and its evolution during shearing is analyzed. Using a miniaturized tension-compression test, the cyclic hardening of the mild steel DX56 and the high strength steel DP600 and the aluminum alloy AA6016 is characterized in 0°, 45° and 90° to the rolling direction. By the identification of an isotropic-kinematic hardening law in combination with the anisotropic flow criterion Yld2000-2d the model's ability to extrapolate the hardening behavior is evaluated. In the last step, the transferability of parameters from the uniaxial stress state to results from a modified shear test is analyzed.

1. Introduction

Shorter development cycles besides an increasing variant- and components-complexity give the numerical pre-design of sheet metal forming processes a highly relevant role in terms of economic manufacturing. According to Roll et al. [1], a targeted use of the finite-element-analysis (FEA) for the pre-design of a forming operation can nowadays save up to 50% of the tool development costs. However, the prognosis of the spring back is still a highly sophisticated area, especially for complex forming processes and lightweight materials like aluminum alloys and high strength steels that exhibit a distinctive spring back behavior. The consideration of the Bauschinger-effect via kinematic hardening models can provide a significant accuracy improvement in the prediction of spring back [2]. The effect is a material specific phenomenon that occurs during cyclic loading and describes the reduction of the yield stress after a load reversal. Since the amount of elastic release during springback is based on the calculated levels of stress, the numerical mapping of the materials hardening is of substantial importance for an accurate prognosis. Especially in processes, where the semi-finished product receives a cyclic loading, like operations with drawbeads, the mapping of the Bauschinger-effect has a major influence on the results of a numerical process prognosis. The characterization of the effect requires test setups that provide a load reversal, like tension-compression tests [3] or cyclic



shear and torsion tests [4]. Kinematic hardening models realize the reduction of the yield stress by a translation of the yield surface via a so-called back stress tensor. The most commonly used models are the non-linear descriptions introduced by Chaboche and Rousselier [5] or Yoshida and Uemori [6]. Besides the fact, that the consideration of the mechanical directional dependence of sheet metals via anisotropic flow criteria is state of the art, the identification of kinematic hardening laws is usually done under a specific stress state and in one direction of the sheet. The influence of anisotropy on the Bauschinger-effect is an only sparsely investigated aspect. While Watanabe et al. [7] identify a significant directional dependency of the effect for dual phase steels, Dell et al. [8] report of an isotropic cyclic hardening behavior for a 2000 series aluminum alloy. Within this research work, the influence of the rolling direction on the kinematic hardening and the ability of an anisotropic model to extrapolate the behavior is analyzed for three different sheet metals. Furthermore, the transferability of material parameters identified under uniaxial loading to a shear stress state is investigated.

2. Experimental and numerical methodology

2.1. Investigated materials and characterization setups

In this research work, the cyclic hardening behavior of three commonly used sheet metals of different material classes is analyzed. The first material is the mild steel DX56, which is a low alloy steel with a comparably low strength but a high formability. The DP600 is a dual phase steel consisting of strength-increasing martensite enclosed in a ferrite matrix. The last material is the precipitation hardenable aluminum alloy AA6016, which is a common lightweight material used for outer skin parts in the automotive industry. All materials have a nominal sheet thickness t_0 of 1.0 mm. In order to analyze the anisotropic material behavior under monotonic loading as well as the identification of an anisotropic yield criterion, standardized uniaxial tension test at a strain rate of 0.004 s^{-1} for steel and 0.007 s^{-1} for aluminum are performed in 0° , 45° and 90° to the rolling direction. The biaxial flow behavior is identified in a hydraulic bulge test that enables a constant strain rate [9], which is chosen in accordance with the uniaxial tension test. The strain in thickness direction is used as the strain equivalent. For the extrapolation of the uniaxial flow curves a transformation on basis of the plastic work is used. Table 1 shows the corresponding mechanical values and the materials Lankford coefficients.

Table 1. Mechanical properties at a plastic strain of 0.05 and Lankford coefficients; $n = 3$

	$\sigma_{0;0.05}$	$\sigma_{45;0.05}$	$\sigma_{90;0.05}$	$\sigma_{b;0.05}^*$	R_0	R_{45}	R_{90}	R_b
AA6016	225 MPa	218 MPa	217 MPa	219 MPa	0.77	0.51	0.73	1.00
DX56	256 MPa	266 MPa	256 MPa	300 MPa	2.03	1.83	2.58	1.00
DP600	613 MPa	625 MPa	625 MPa	628 MPa	0.95	0.92	1.21	1.00

* in thickness direction

For the characterization of the cyclic hardening behavior and in this context the analysis of the Bauschinger-effect, a miniaturized tension-compression test [3] (TCT) as well as a cyclic shear test [10] (CST) are used. The setups are installed in a universal testing machine Z100 (Zwick GmbH & Co. KG, Ulm, Germany). During the process the force is measured by a 100 kN load cell, which is mounted in the traverse of the testing machine. The local strain in the 4.0 mm^2 deformation area of the tension-compression test specimen as well as in the 7.5 mm^2 deformation area of the modified ASTM shear test specimen is detected via the optical strain measurement system ARAMIS (GOM GmbH, Braunschweig, Germany). To hinder buckling as well as localize the plastic deformation the specimens are hydraulically clamped between stabilization plates. For both characterization tests, a strain rate, which is in accordance with the uniaxial tension test, is chosen. In case of the tension-compression setup, the materials are tested at 0° , 45° and 90° to the rolling direction (RD). To ensure a loading in the principal axis, the shear specimens are extracted in 45° to the rolling direction. Since the Bauschinger-effect is known to have a material specific dependency on the pre-strain [4] all materials are tested at equivalent pre-strains of 0.03, 0.06 and 0.08 ± 0.01 . For a statistical coverage, every configuration is repeated three times.

2.2. Material modeling and identification of the isotropic-kinematic hardening

The anisotropic yielding under monotonic loading of the investigated materials is mapped via the yield criterion Yld2000-2d from Barlat et al. [11], which is implemented in the material card *MAT_133 in the FEM Software LS-DYNA of the Livermore Software Technology Corporation. Parameters are identified on basis of the values from table 1. The cyclic hardening behavior is modeled via a combination of the isotropic hardening according to Hockett and Sherby [12] and the kinematic model from Chaboche and Rousselier [5]. In this kinematic hardening law the backstress-tensor $\underline{\alpha}$ is composed by a summation of multiple exponential functions according to the equation in figure 1 c).

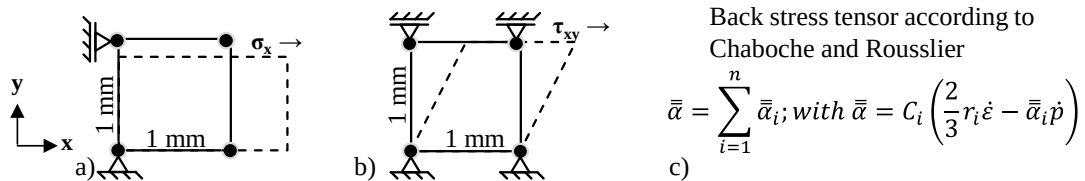


Figure 1. One-element-models: a) tension-compression and b) simple shear; d) hardening model according to Chaboche and Rousselier

C_i and r_i are the model's parameters, while p is the accumulated plastic strain. In this research work two back stress terms are used, which leads to four kinematic hardening parameters in sum. The kinematic parameters are identified via an inverse method using the LS-OPT optimization software of the Livermore Software Technology Corporation. In this method, the global error between a simulated stress-strain curve and the experimental data is minimized by a stepwise adaption of the material model. Since the optimization procedure requires a huge number of single simulations, both test setups are simplified via one-element-models as displayed in Figure 1 a) and b). The selection of parameters is based on a d-optimal design space. The minimization is done with help of a polynomial model of linear order. The maximum number of iterations is set to 30.

3. Analysis of the anisotropy of the Bauschinger-effect

As already displayed in table 1, all investigated materials exhibit only slight differences in the directional dependent yield stress of fewer than 4 %. This is also reflected in results from the tension-compression test in figure 2, which shows one representative curve of the three retries for each rolling direction. For all three materials only small to none differences can be detected. Both under tension as well as compression, the mild steel DX56 shows no meaningful variance between the cyclic curves in 0°, 45° and 90° to the rolling direction.

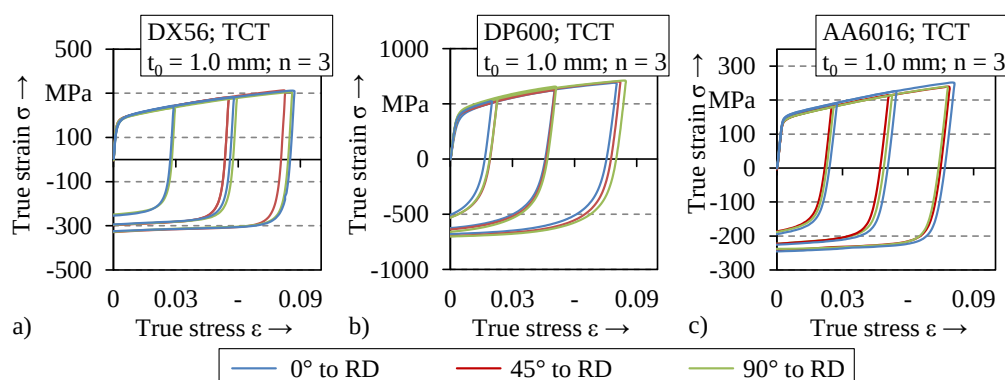


Figure 2. Cyclic true stress - true strain Curves from the tension-compression test: a) DX56; b) DP600; c) AA6016

While the DX56 shows only a slight elastic-plastic transient area and immediately regains the stress level that existed before the load reversal, the dual phase steel has a very distinctive transient zone.

The cyclic curves of the DP600 from 90° to RD show a slightly higher stress level, which is however compared to the experimental standard deviation of ± 7.0 MPa not significant. The Bauschinger-effect of the aluminum alloy AA6016 has a similar characteristic to the one of the mild steel DX56. With respect to the anisotropy, a slightly higher yield stress in rolling direction of about + 10.0 MPa compared to 45° and 90° can be detected. After the load reversal, the difference between the curves reduces to less than 5.0 MPa. One simple way to quantify the Bauschinger-Effect is the ratio - denoted as Bauschinger-coefficient (BC) - of the true stress before the load reversal to the yield point after the load reversal, which is in this research work defined at a reversal plastic strain of 0.002. Figure 3 gives an overview of the Bauschinger-coefficients with respect to the rolling angle and the pre-strain. The DX56 has the highest Bauschinger-coefficient in a range of 0.73 to 0.86 and therefore the smallest Bauschinger-effect within the analyzed materials. With respect to the standard deviation, no meaningful dependency on the rolling direction can be identified. However, the coefficient slightly decreases with an increasing amount of pre-strain. For instance, in 0° to RD, the value reduces from 0.87 ± 0.04 at a pre-strain of 0.03 to 0.78 ± 0.05 at a pre-strain of 0.08. The reduction of the Bauschinger-coefficient with increasing plastic pre-strain is in accordance with the results from Yin et al [4]. With BC-values of under 0.6, the dual phase steel provides the highest reduction of the yield stress after the load reversal. For all three pre-strains, the coefficient of 90° is slightly higher (+ 0.02 to + 0.10) than in the other directions. However, the pre-strain has a greater influence on the coefficient than the rolling direction. Starting at an average value of 0.57 for a pre-strain 0.03 the value decreases by 38 % to approximately 0.33 at pre-strains of 0.08.

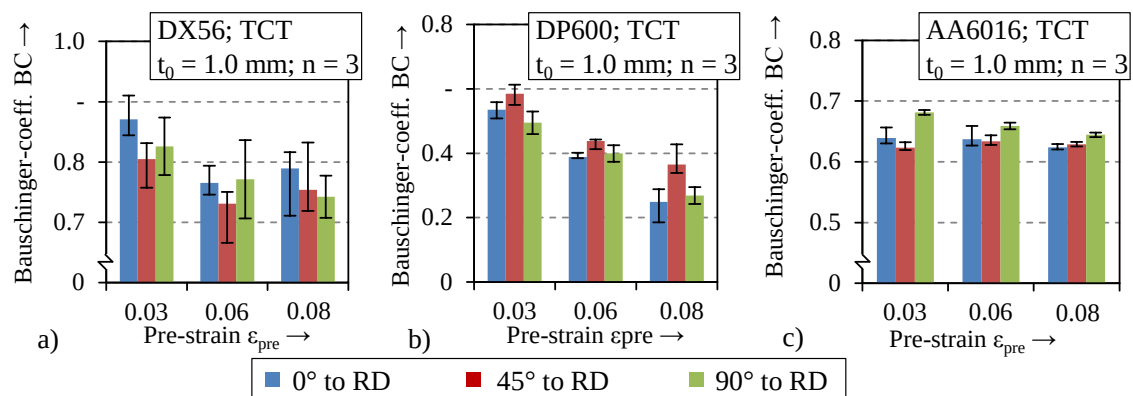


Figure 3. Bauschinger-coefficients with regard to the pre-strain and rolling direction: a) DX56; b) DP600; c) AA6016

In case of the aluminum alloy AA6014, the Bauschinger-coefficients at 0° and 45° to the rolling direction are quite similar. Independently from the induced pre-strain, the BC-value lies in a range of 0.62 and 0.64. The value of 90° to RD is principally higher than the coefficients from the other rolling directions. This results from the higher stress levels under tension and the fact, that the difference to the curves from the other rolling direction is reduced after the load reversal. In contrast to the coefficients from 0° and 45°, a significant dependence from the pre-strain can be detected. At a pre-strain of 0.03, the BC-value is on average at 0.68 ± 0.02 . Increasing the pre-strain up to 0.08 the value is reduced to 0.64 ± 0.01 . In summary both the cyclic curves as well as the Bauschinger-coefficients show for all investigated materials only a slight or rather no significant influence from the rolling direction. Especially in case of the steel materials, the pre-strain has a major influence on the cyclic material behavior than the orientation of the semi-finished product.

4. Transferability of parameters from different rolling directions

Since a material characterization can never cover the full range of stress and strain states of a real forming process, used numerical models must be able to extrapolate the material behavior realistically. Figure 4 displays for the mild steel DX56 the numerical modeling of the cyclic hardening behavior

with respect to the rolling direction and the transfer of a kinematic parameter set identified in 0° to RD. A pure isotropic model clearly overestimates the stresses after the load reversal with an average error that lies -depending on the orientation of the sheet- in between 25 to 27 MPa. With respect to the average reached stresses this is an error of circa 10 %. In a finite-element-analysis of a forming process, the calculated local stresses would be too high and thus no accurate prognosis of the springback possible. By the application of the kinematic hardening law, the error can be reduced to less than 17 MPa, which is an improvement of 35 %. Corresponding to the generally coincident cyclic hardening curves, the transfer of the kinematic hardening model from 0° to RD to the other rolling directions leads to similar mean absolute errors (14 to 17 MPa) like achieved from parameters that are identified with respect to the rolling direction.

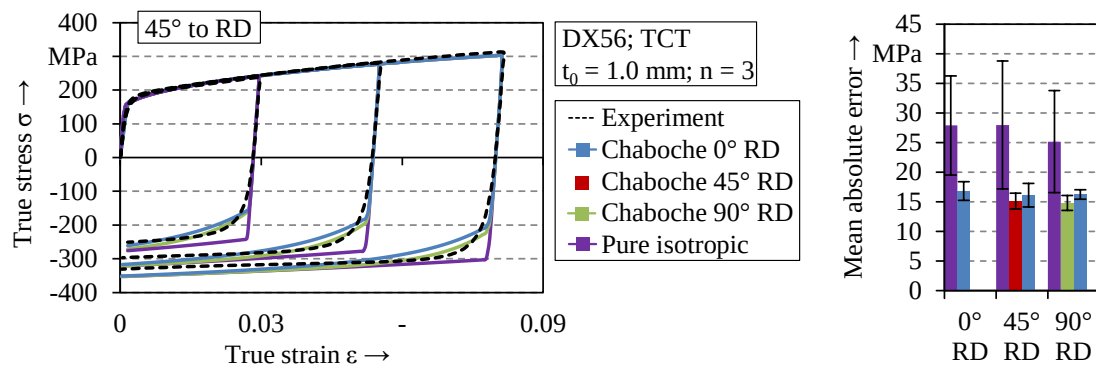


Figure 4. Modelling of the kinematic hardening behavior with respect to the rolling direction for the mild steel DX56

Based on the highly developed elastic-plastic transition region of the dual-phase steel DP600, it is not possible to correctly reproduce its cyclic hardening behavior with a purely isotropic hardening law. As visible in figure 5 (left), the isotropic model leads to an over prediction of the stresses with an average error of 140 MPa. In correspondence to the average stress levels this leads to an error of nearly 30 %, which is three times more than in case of the mild steel.

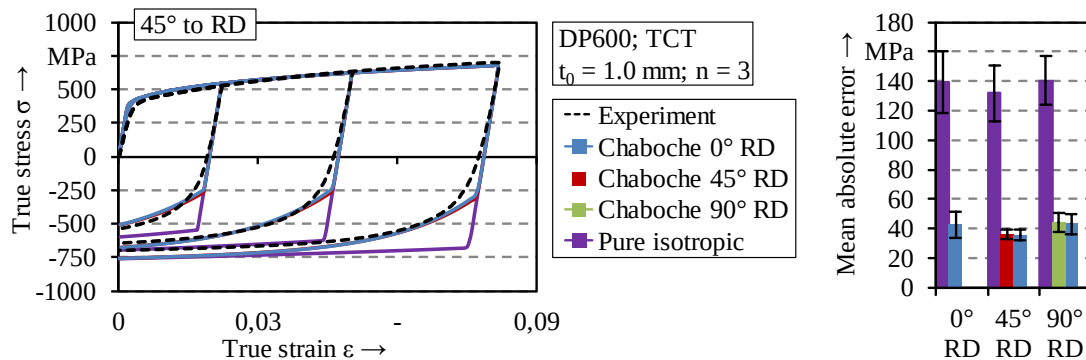


Figure 5. Modelling of the kinematic hardening behavior with respect to the rolling direction for the dual phase steel DP600

Especially in the transient zone, the stresses are overestimated by 100 % and more. Independent of the rolling direction the use of the kinematic hardening model according to Chaboche and Rousselier [5] significantly improves the numerical prediction quality and reduces the global error by nearly 70 % to circa 40 MPa. The parameter set identified in 0° to RD provides a quite good extrapolation of the cyclic hardening behavior in 45° and 90° to RD. With respect to the cyclic stress-strain curve in 45° to RD as well as the mean absolute errors, displayed in figure 6 (right), there is no significant difference to a parameter set that is adapted on basis of the specific rolling direction.

According to figure 6, the use of a pure isotropic hardening law leads to the aluminum alloy AA6016 to a wrong prognosis off the stress level similarly to the steel materials. After the load reversal, the global mean error lies in a range of 44 to 52 MPa. Based on the average level of reached stresses stress this leads to an error of circa 30 % that is comparable to the discrepancy that is achieved for the dual phase steel. The identification of the kinematic hardening model in 0° to RD is sufficient to describe the cyclic hardening behavior in all three investigated rolling directions. Thus, there is no significant difference between the mean absolute arrows of the directly identified models and the parameter set identified in 0° to RD. For all kinematic models, the global arrow can be reduced by nearly 75 % to fewer than 15 MPa.

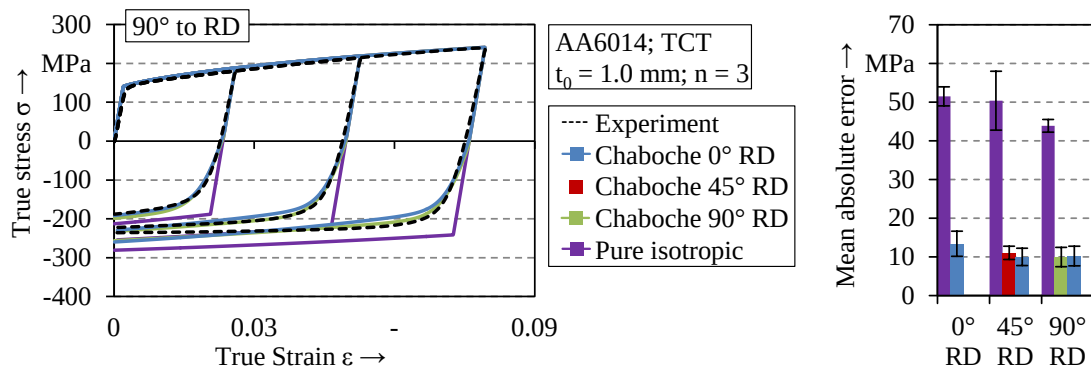


Figure 6. Modelling of the kinematic hardening behavior with respect to the rolling direction for the aluminum alloy AA6016

5. Transferability of parameters from uniaxial loading to a shear stress state

Considering a complex forming operation not only the materials dependency on the rolling direction but also its stress state related hardening and the ability of the applied model to extrapolate this behavior is of major importance for a correct process prognosis. Figure 7 shows the transfer of the kinematic hardening parameters of the mild steel DX56 from the tension-compression test to the results of the cyclic shear test. Furthermore, the comparison to a parameter set directly identified on the cyclic shear data is presented. The monotonic hardening curve before the load reversal is mapped quite well with an error of fewer than 6 %, which indicates a respectively good approximation quality of the anisotropic yield criterion Yld2000-2d.

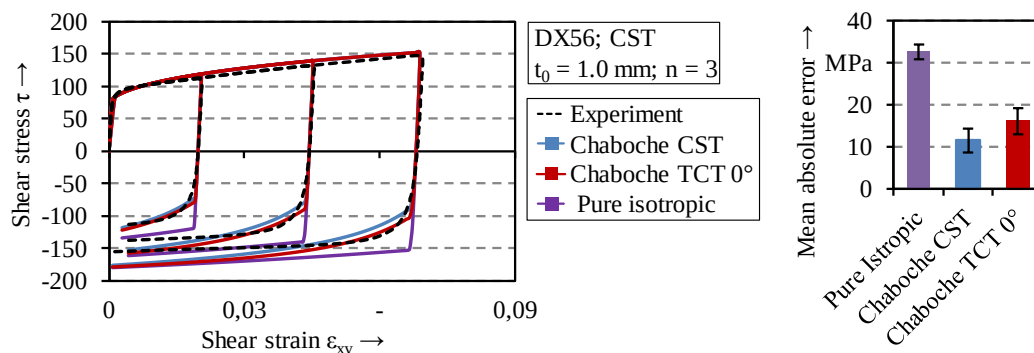


Figure 7: Cyclic shear curves and their numerical mapping for the DX56

Like in the results of the tension-compression test, also the shear curves show a Bauschinger-effect. Thus, the pure isotropic hardening law evidently overestimates the stress level after the load change, particularly in the transient area. The global error of the pure isotropic hardening law is at 32 ± 1.6 MPa. By the application of the kinematic hardening law, the error can be reduced under 20 MPa. The parameter set from the uniaxial tension-compression test slightly overestimates the Bauschinger-

effect in the shear stress state, especially at higher pre-strains. Comparing the mean absolute error of both models, the identification of the hardening law on basis of the shear stress data gives with 12.0 ± 1.5 MPa a better approximation than the parameter set from the uniaxial tension-compression test, where the global error is at 16.0 ± 2.8 MPa. The dual phase steel DP600 leads to a quite similar result, displayed in figure 8. A clear Bauschinger-effect can be detected in the cyclic shear data and thus the pure isotropic model overestimates the stress level, with an average error of 12.2 ± 2.8 MPa. Also here the direct identification of a parameter set provides a better approximation results than the transfer of the tension-compression test parameter set, which leads to an average error of 40 ± 12 MPa.

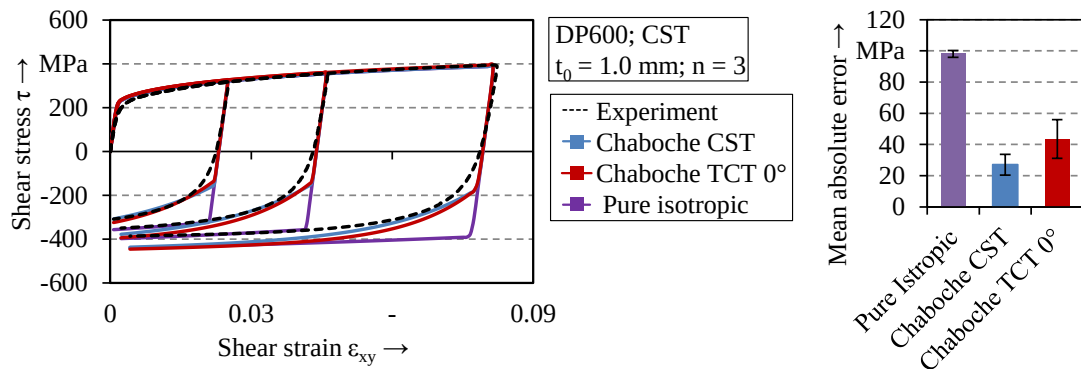


Figure 8. Cyclic shear curves and their numerical mapping for the DP600

In case of and the aluminum alloy, the parameter-set from the tension-compression significantly overestimates the Bauschinger-effect in the shearing stress state, as can be seen in figure 9 on the left side. Especially at respectively high pre-strain of 0.08, the stress level is underestimated by 30 MPa and more. In comparison to a pure isotropic hardening parameter set, where the mean absolute error is at 13.5 ± 4.1 MPa, no advantage can be achieved. The direct identification of parameters on basis of the shear stress-strain data can significantly reduce the global error to less than 5 MPa.

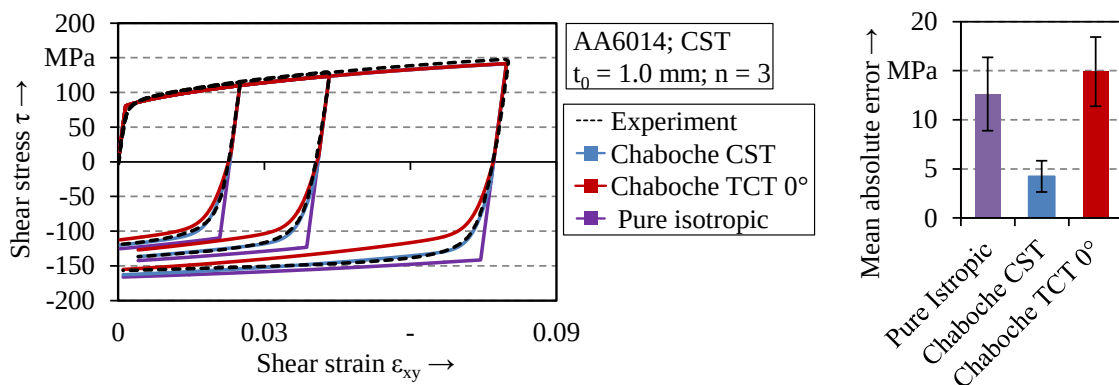


Figure 9. Cyclic shear curves and their numerical mapping for AA6016

For all three sheet metal materials, there is a misfit between the calculated cyclic material behavior on basis of tension-compression data and the cyclic data from the modified ASTM-shear test. The increase of the approximation quality achieved by a directly on the shear data identified parameter set is for the two steel materials at the edge of being significant. For the aluminum alloy, there is a major difference between the extrapolated data and the experimentally detected cyclic behavior. A possible explanation for the discrepancy could be the calibration of the yield criterion, which was done without the data of the shear test. Furthermore, a transformation of the biaxial data on basis of the plastic work could lead to different results. The improvement of a consideration in the calibration of the yield criterion as well as the impact on the results of actual a sheet metal forming operation has to be analyzed.

6. Conclusions

In this research work the Bauschinger-effect of three commonly used sheet-metal materials, the mild steel DX56, the dual phase steel DP600 and the and a minimum alloy AA6016, is analyzed with respect to the rolling direction. Furthermore, the transferability of hardening parameters identified in an uniaxial loading condition to a shear stress state is evaluated. For all investigated materials no significant dependency of the kinematic hardening behavior with respect to the rolling direction can be detected. While a kinematic hardening law definitely leads to a significantly better approximation of the cyclic hardening behavior than a pure isotropic formulation, the use of an anisotropic yield criterion is sufficient to extrapolate the directional dependent cyclic behavior. The transfer of parameters from the uniaxial tension test to the results of a modified ASTM-shear test leads to substantial deviations for all three materials. However, the impact of this stress state dependent hardening behavior and its numerical approximation on the results of a calculation of a sheet metal forming operation has to be analyzed.

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