Evaluation of kinematic hardening models for multiple stress reversals under continuous cyclic shearing and multi-step bending

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Abstract:

In complex sheet metal forming processes the material undergoes various strain path changes, for instance, during the passing of a drawbead or a radius. Based on the Bauschinger effect that describes the material's specific decrease of the yield stress after a load reversal, the resultant hardening behavior significantly differs from that of a monotonic loading condition. For a reliable numerical process design, especially in springback analysis, a consideration of this effect is essential. Within this contribution, the evolution of the material behavior under cyclic loading is investigated with consecutive cyclic shearing of DP-K54/78+Z in a modified ASTM shear test. Moreover, the kinematic hardening models according to Chaboche-Rousselier and Yoshida-Uemori are identified. In this context, the influence of the yield criterion and the capability of the different hardening models are analyzed. The applicability of the identified parameters is finally evaluated in a multi-step bending process.

Keywords:

metal forming, modeling, kinematic hardening

Introduction

Driven by modern requirements on the shape of sheet forming products, e.g. sharp edges and narrow manufacturing tolerances, an exact numerical process design becomes increasingly important. Within this context, the predictability of sheet forming processes is essential to reduce time and cost [1]. Many sheet forming parts undergo complex stress paths and strain path changes, which lead to a shift of the material behavior.

This effect results in a reduction of the yield stress after pre-loading and is known as Bauschinger effect or a kinematic hardening behavior. Disregarding the evolving material properties, effects a falsification of the predicted numerical springback behavior of the forming process. As mentioned by Wagoner et al. [2], springback means the elastically-driven change of the shape of the part geometry after the forming process. This is affected by a recovery of introduced stresses after removing the part out of the tool. Hence, the numerical result of the part's springback simulation is highly influenced by the introduced stresses and therefore by the given material parameters, e.g. the yield stress and the hardening behavior. Sun et al. [3] investigated the proportional and non-proportional hardening behavior of dual-phase steels and found out that the prediction of draw-bend springback is improved by a factor of three considering a kinematic hardening component in the numerical simulation.

Since the isotropic hardening behavior is described through a flow curve normally determined by uniaxial tensile tests, the kinematic hardening behavior is characterized by cyclic tension-compression tests [4], cyclic bending tests [5] or cyclic shear tests [6]. Whereas a direct identification of kinematic hardening laws is possible in case of the tension-compression test and the cyclic shear test, an inverse identification procedure is needed in case of the cyclic bending test [7]. However, the bending test, e.g. three-point bending test, can further be used to investigate the springback behavior of the material after various load steps [8].

The shear test has the advantage of higher reachable plastic strains without the risk of necking or buckling. For this, different test setups to realize simple shear tests, e.g. Miyauchi [9] or simple shear testing according to ASTM B831 [10], were developed. An overview of the different shear tests is given by Yin et al. [11]. Moreover, Suttner et al. [12] showed a good accordance of the results of the cyclic shear test with a modified ASTM specimen to the uniaxial tension-compression tests with a miniaturized tensile specimen.

The kinematic hardening behavior is adopted to improve the accuracy of sheet metal forming simulations. One of the first kinematic hardening laws is presented by Frederick et al. [13] to consider permanent softening of the material behavior induced by the Bauschinger effect. Because advanced high strength steels show a transient softening behavior after load reversal, more complex models are needed to map the material behavior. Therefore, Chaboche et al. [14] proposed a modification of the Armstrong-Frederick model, which extended the formulation of the model with a summation of Armstrong-Frederick terms. In this context, the advantage of the Armstrong-Frederick type models is a direct linkage of the kinematic hardening laws to conventional material models with a yield criterion and an isotropic hardening law. A review of different kinematic hardening laws is presented by Chaboche [15]. Besides, Yoshida et al. [16] presented an isotropic-kinematic hardening approach, which additionally considers workhardening stagnation during plastification after load path changes. A classification of the different sorts of hardening laws is described in [2], where a differentiation between Armstrong-Frederick type, Multi-surface-type, e.g. Yoshida-Uemori model, and other newer approaches as the alternative plasticity formulation with a homogeneous yield function-based anisotropic hardening (HAH) presented by Barlat et al. [17] is done. Other approaches as presented by Yoshida et al. [18] deal with the evolution of anisotropy, the continuous variation of the yield surface and the Bauschinger effect during forming with the advantage of a reduced number of needed material parameters.

Within this contribution, a cyclic shear test is carried out to characterize the kinematic material behavior of an advanced high strength steel DP-K-54/78+Z. Moreover, the parameters of the kinematic hardening models proposed by Chaboche et al. [14] and Yoshida et al. [16] are identified for one and two load reversals to investigate the evolution of the kinematic hardening behavior. Additionally, the influence of two commonly used yield criteria Barlat'89 according to Barlat et al. [19] and Yld2000-2d according to Barlat et al. [20] are investigated. The isotropic hardening behavior is described by the isotropic hardening law proposed by Hockett et al. [21]. A validation of the identified material models is done with the help of a cyclic bending test. Beside the advantage of a robust test setup, the used cyclic bending test can be used to generate a U-Profil for the estimation of the springback behavior after various loading sequences [22].

1 Identification of kinematic hardening parameters

1.1 Experimental setup

The planar simple shear test based on a built-in tool according to Merklein et al. [23] is predicated on the ASTM standard B831 and used for the characterization of the cyclic material behavior under simple shearing. The tool device is mounted in a universal testing machine (Z100, Zwick GmbH & Co. KG) with a 100 kN load cell. The clamping device consists of two hydraulic clamps with a maximum clamping pressure of 40 MPa. In contrast to the original ASTM setting and the original shear specimen, the specimen is modified for cyclic testing and stabilizer plates are added to prevent the specimen from buckling during testing. Moreover, the stabilizer plates are placed near the relevant measurement zone to avoid a large rotation of the shear zone. The tests are performed at room temperature with an equivalent strain rate of 0.004 1/s and three retries (n = 3) for each test configuration.
The tensorial shear strain ε_{xy} is detected with an optical strain measurement system and a two-dimensional camera with a resolution of 4 megapixels. The shear specimen is extracted by laser cutting (TruLaser Cell 7020, Trumpf GmbH + Co. KG) in 45° to the rolling direction of the sheet with a sheet thickness of 1.0 mm. The shear zone length is set to 4.72 mm, while the shear zone width is 1.6 mm.

1.2 Material models and numerical identification strategy

The results of the cyclic shear tests are used to identify various kinematic hardening laws for the investigated dual-phase steel. Providing a huge variety of implemented hardening models and yield criteria the FEM-software LS-DYNA® in revision 7 is chosen for the numerical modeling of the material behavior and the applied processes.
First of all, the influence of the chosen yield criterion is investigated. Therefore, two implemented material cards **`*MAT_036`** with the yield criterion Barlat'89 and **`*MAT_133`** with the yield criterion Yld2000-2d are chosen. To eliminate the influence of the isotropic hardening model, the isotropic hardening law according to Hockett et al. [21] is chosen in case of both material models. The isotropic hardening law is identified with the help of uniaxial tensile tests in 0° to the rolling direction, while uniaxial tensile tests in 0°, 45° and 90° to the rolling direction are carried out to determine the Lankford coefficients for the consideration in the Barlat'89 model with an exponent m of 8. Supplementary, biaxial tensile tests with a cruciform specimen are performed to identify the more complex yield criterion Yld2000-2d (m = 5). The exponents of 8 for Barlat'89 and 5 for Yld2000-2d are chosen to receive a comparable hardening behavior and a good accordance of the hardening evolution.
To estimate the effect of kinematic hardening, the investigations are additionally extended in a second step with the adaption of the kinematic hardening model according to Chaboche et al. [14]. In order to analyze the influence of the chosen kinematic hardening law, the material model **`*MAT_226`** is utilized, which considers the complex isotropic-kinematic hardening model according to Yoshida et al. [16]. A summary of the used material cards and their underlying material models as well as the in this research utilized abbreviations is given in table 1:

Material card	Yield criterion	Isotropic hardening	Kinematic hardening	Abbreviation
`*MAT_036`	Barlat '89	Hockett-Sherby	none	*MAT_036_ISO
			Chaboche-Rousselier	*MAT_036_CHAB
`*MAT_133`	Yld2000-2d	Hockett-Sherby	none	*MAT_133_ISO
			Chaboche-Rousselier	*MAT_133_CHAB
`*MAT_226`	Barlat '89	Yoshida-Uemori		*MAT_226_YOSH

Table 1: Used material cards and included models

The identification of the two investigated hardening laws is done by an inverse procedure using the optimization software LS-OPT® in combination with the FEM-solver LS-DYNA®. Based on FEM-simulations this process minimizes the error between experimental shear stress-strain curves and simulative results via the adaption of the appendant material parameters. Since the invers parameter identification is - in comparison to analytical approaches - a relative time- and CPU-intensive process, a one-element simple shear model, as displayed in figure 1 a), is used.

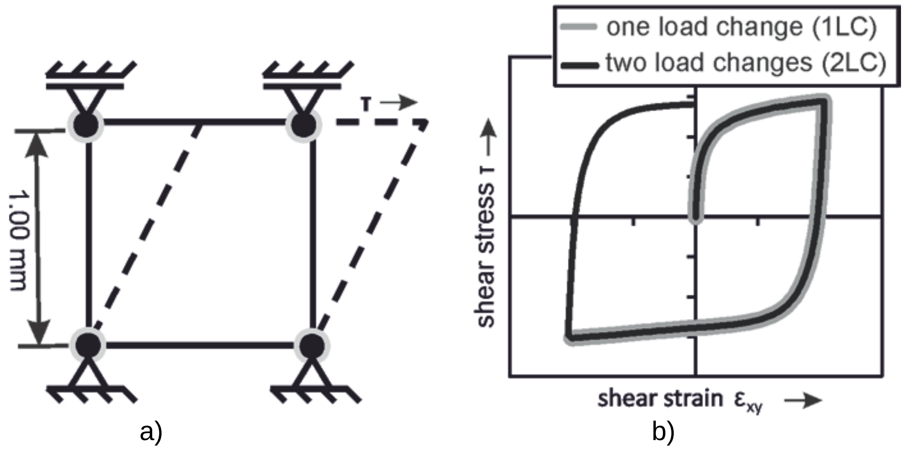


Fig.1: a) one-element simple shear element; b) different identification zones

The experimental shear strain can be emulated by the one-element simple shear model via a translation of the upper two nodes, which are constrained as floating bearings. The prescribed translation corresponds to the double of the measured shear strain ε_{xy}.
Since the duration of an inverse parameter identification strongly depends on the effective time for the calculation of the underlying simulations, the necessity of an identification based on multiple load changes is observed. Therefore, the used material models are adapted on the basis of one and two load changes (1LC or 2LC). The respective areas are illustrated in figure 1 b). Within this analysis the ability of the used material to extrapolate the materials hardening behavior can be evaluated additionally.
Due to the hysteresis stress-strain curves, the curve-mapping algorithm (CM) implemented in LS-OPT® is applied to quantify the deviation between the numerical prediction and the experimental data. The design of the parameter space is done by the use of a polynomial metamodel with a linear order and a d-optimal point selection. In every case a maximum of 50 iteration slopes is calculated to receive the final set of parameters.

1.3 Evaluation of the kinematic hardening models under multiple load reversals

1.3.1 Applicability of the one-element model and influence of the yield criterion

An inverse identification procedure is mostly a time consuming procedure. To reduce the cost of time an one-element model is taken as a basis of the evaluation process. Therefore, a fully integrated (ELFORM 16) shell element with an edge length of 1.0 mm is chosen as seen in figure 1 a). In a first step, the influence of the chosen yield criterion is investigated and the result is shown in figure 2 a) compared to the experimental result of the shear test. In contrast to this, the material models are extended with the kinematic Chaboche model to model the transient hardening behavior and the Bauschinger effect. The identification procedure is done for one load change (1LC) and the received parameters are shown in table 2.

Model	Yield criterion	C_1	r_1	C_2	r_2	CM
*MAT_036_CHAB_1LC	Barlat `89	28.256	183.008	155.782	328.972	$0.363*10^{-3}$
*MAT_133_CHAB_1LC	Yld2000-2d	24.676	213.479	153.356	298.394	$0.355*10^{-3}$

Table 2: Chaboche-Rousselier parameters in decency of the yield criterion

As illustrated in table 2 the results for the C and r parameters are slightly differing for the investigated materials, but almost in the same range. In addition, the curve mapping (CM) parameter shows no significant variation. The result of the invers identification procedure of the kinematic hardening Chaboche law is presented in figure 2 b) for the investigated material models ***MAT_036** and ***MAT_133** versus the experimental result.

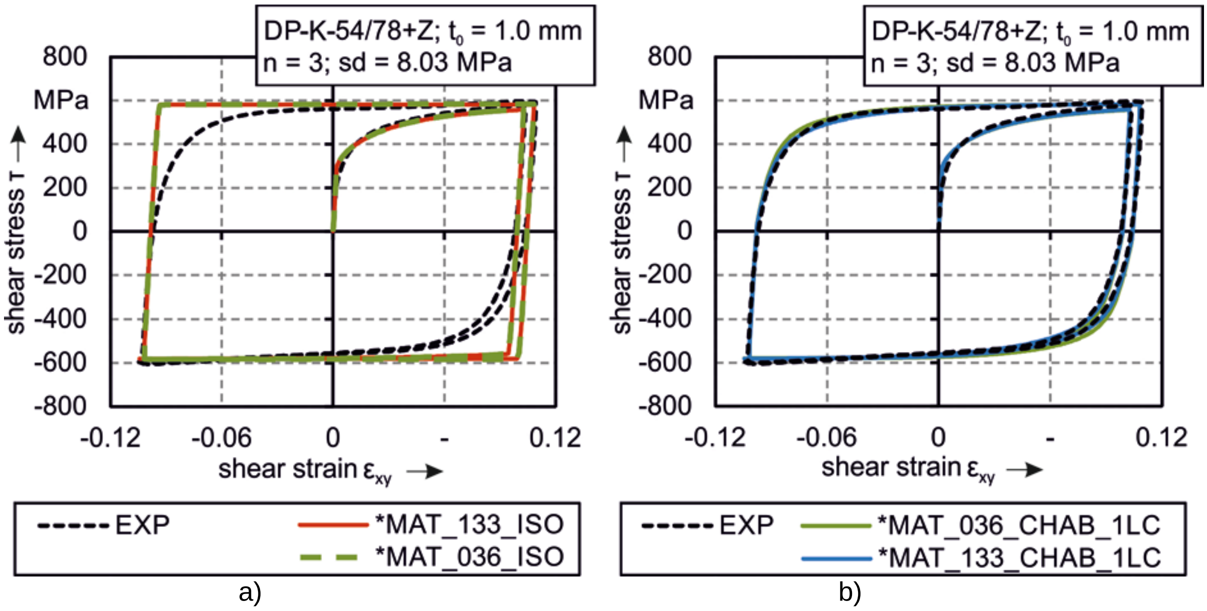


Fig.2: Comparison of the experimental data and the simple shear model in dependency of the yield criterion: a) Pure isotropic hardening; b) Chaboche-Rousselier hardening

As seen in figure 2 a), no significant variation between the chosen yield criteria is depicted. Moreover, a good accordance of the isotropic hardening behavior compared to the experimental shear curve is observed. In contrast to this, the transient hardening behavior and the kinematic hardening evolution is not considered in a pure isotropic formulation, which leads to a large deviation of both numerical results compared to the experimental result after the first load change (1LC) and the second load change (2LC). In addition, no permanent softening is observed for higher levels of plastification during shearing.

In figure 2 b), the results of the shear curves considering an isotropic-kinematic hardening behavior are presented. Both investigated models agree well with the experimental shear curve, while the outcome of **`*MAT_036`** shows a slight deviation of the transient hardening behavior compared to the experimental result. However, the material behavior after one load change (1LC) and two load changes (2LC) is well mapped with the identified isotropic-kinematic hardening model.

1.3.2 Identification on multiple load reversals

Since simplified material characterization tests never cover the whole stress-strain states and changes that a sheet metal experiences during a complex forming operation, the knowledge, in how far the underlying material models are able to extrapolate the material behavior is essential for a reliable simulation. Against this background, the capability of the two hardening models to predict multiple load changes and thereby the necessity of an identification at several load cycles is observed.

Table 3 lists the parameters of the Chaboche-Rousselier model identified at one (1LC) and two load chances (2LC). The parameter sets significantly differ from each other. However, with respect to the cyclic shear stress-strain curves, which are displayed in figure 2 a), no major difference between the prediction of the models can be seen. This leads to the assumption that the parameters of the hardening model are not definite with respect to the predicted stress-strain behavior. The identification at one load change is sufficient to describe a second and even a third load change quite satisfactorily. An expansion of the identification area to the second load cycle (2LC) comes with no enhancement of the numerical prediction quality of the shear curve.

Model	C_1	r_1	C_2	r_2	CM
*MAT_036_CHAB_1LC	28.256	183.008	155.782	328.972	$0.363 \cdot 10^{-3}$
*MAT_036_CHAB_2LC	33.549	246.160	418.761	265.697	$0.364 \cdot 10^{-3}$

Table 3: Chaboche-Rousselier parameters in decency of load changes

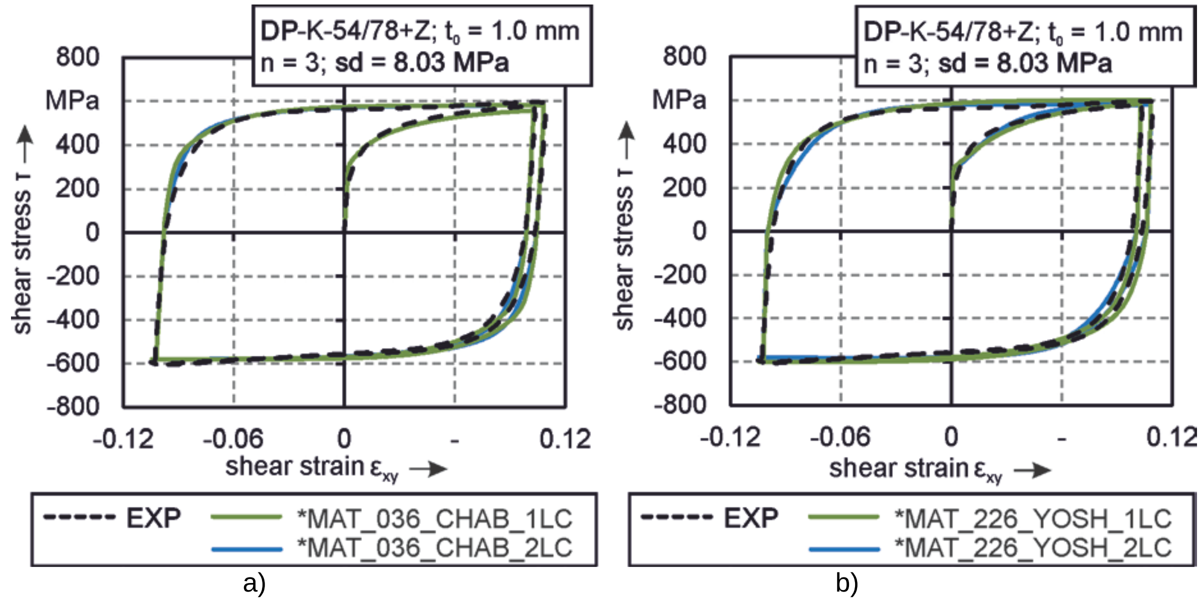


Fig.3: Comparison of the experimental results and the numerical simple shear curves in dependency of the yield criterion: a) Pure isotropic hardening; b) Chaboche-Rousselier hardening

In case of the hardening model according to Yoshida et al. the results are quite similar. Despite the varying material parameters, displayed in table 4, the shear stress-strain curves that are shown in figure 3 b) are nearly coincident. Also here the parameter set identified at one load cycle enables a quite good prognosis of the subsequent stress-strain curve. The identification on the parameters of two load changes leads to no obvious improvement.

Model	Y	B	C	m	K	b	h	CM
*MAT_226_YOSH_1LC	515.400	515.400	21.072	69.416	497.835	17.565	0.650	$0.11 \cdot 10^{-2}$
*MAT_226_YOSH_2LC	515.400	534.428	84.338	12.462	250.116	285.313	1.000	$0.15 \cdot 10^{-3}$

Table 4: Yoshida-Uemori parameters in dependency of load changes

Comparing the two hardening laws regarding the numerical prediction quality no clear preference can be seen. Both the isotropic-kinematic hardening law Yoshida-Uemori and the kinematic Chaboche-Rousselier model are able to describe the hardening behavior, e.g. the transient hardening evolution, of the observed dual-phase steel under shear deformation with an equal quality. However, based on its complexity and the six parameters that have to be identified, the Yoshida-Uemori model takes nearly the double of identification time at one load change (figure 4). In this context it has to be noted, that the singular simulations of one iteration step were calculated simultaneously and the relative calculation time is referred to the identification time of the Chaboche-Rousselier model at one load change. The extension on a second load cycle leads in both cases to an increase of the identification time. Nevertheless, this increase is more distinctive in case of the Chaboche-Rousselier model. The calculation of the metamodels and the design space during the identification procedure is - resulting on the fewer variables - less time consuming as in the matter of the Yoshida-Uemori model and thus the increase of the simulation time comes more into account.

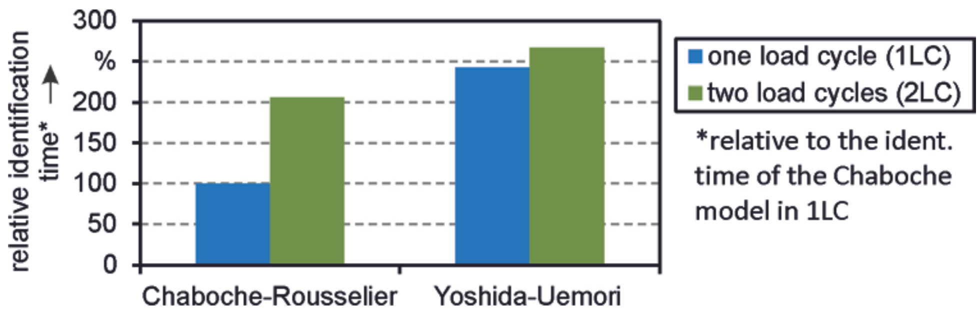


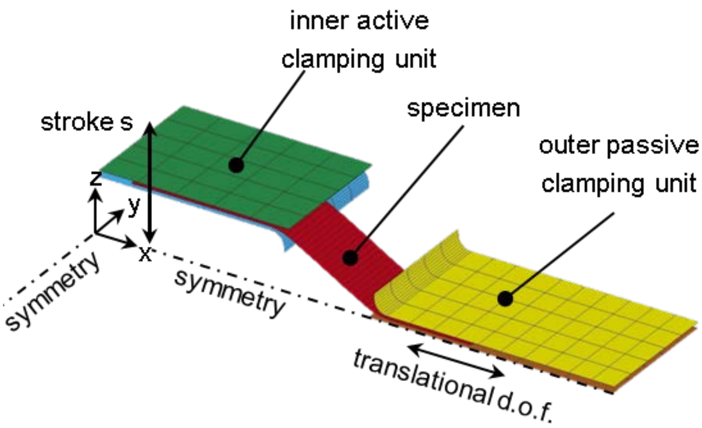
Fig.4: Relative time for the inverse identification of the hardening models

2 Validation under cyclic bending

The observed capability of both hardening laws to describe the materials proceeding hardening behavior is at this stage only proven for the simple shear deformation. Therefore, the transferability of the results and application of the parameters is examined in a cyclic bending operation.

2.1 Experimental and numerical Setup

To produce a springback inherent profile and to approximate the stress-strain history that a sheet metal experiences during the passing of a radius or a drawbead cyclic bending tests are performed. The used symmetrical test setup consists of a central clamping unit, which is attached to the traverse of a universal testing machine (Z100, Zwick GmbH & Co. KG) and two passive clamping units guided on a linear bearing. During the test, the central clamping unit moves vertically, while the outer units follow the motion and the rectangular specimen (figure 5 b) gets bend around bending radii. Using 3 mm bending radii and a stroke cycle of 0-16-0-16-5 mm three load changes with a maximum strain of $\varepsilon = 0.12$ on the outer side of the sheet are realized. To guarantee a concluded springback process the specimen is digitalized via a 3d-digitizer after one week of stress recovery.



a)

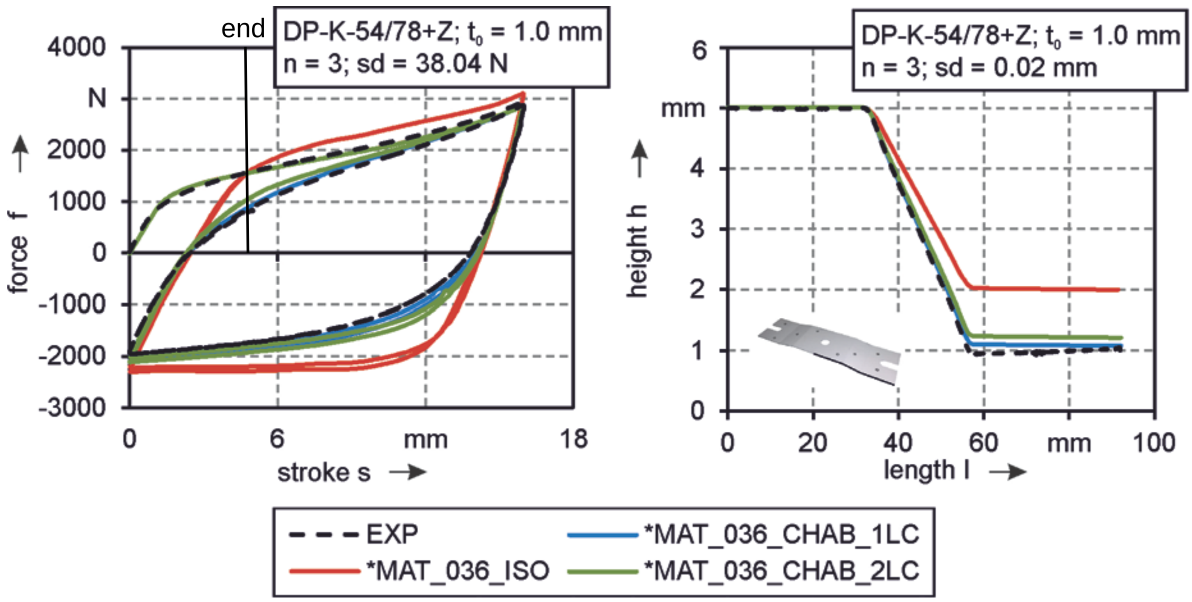
b)

Fig.5: a) FEM-model of the cyclic bending test; b) Specimen of the cyclic bending test with optical measurement points

A validation of the identified hardening models is done by the comparison of the experimental data and the results of a FEM-simulation regarding the force vs. stroke curve and the geometry after springback. Utilizing the symmetry of the test setup a quarter FEM-model, which is displayed in figure 5 a), is used. The bending tools are modeled as rigid bodies, whereas the specimen is discretized via fully integrated shell-elements (ELFORM 16) with eleven integration points across the sheet thickness. The simulation of the forming process as well as the subsequent springback calculation is done implicitly with use of the LS-DYNA® solver in revision 7.

2.2 Springback analysis

Figure 6 shows the experimental results and the numerical prediction of the bending process using the kinematic hardening Chaboche-Rousselier model as well as a pure isotopic hardening model. In consideration of the force vs. stroke curves, illustrated in figure 6 a), the importance of kinematic hardening laws becomes clear. The pure isotropic hardening law overestimates the bending force especially in the transient areas. At the end of the bending process, which is terminated after three load changes in the transient area at a stroke of s = 5 mm, the experimental force is at 820 N. The pure isotropic hardening model overestimates the force by a factor of approximately 100 % to 1639 N. Due to the wrong prediction of internal stresses, the calculated springback, as it is displayed in figure 6 b), is also overvalued. The experimental specimen shows a reduction of the height of nearly 1 mm after springback, whereas the pure isotropic hardening predicts a springback of closely 2 mm. With the use of the kinematic hardening parameters the numerical prediction quality significantly increases. The parameters on the basis of the consecutive shear test are able to describe the bending force during the three load changes with a high accuracy.



a) b)

Fig.6: Validation of the Chaboche-Rousselier parameters in the cyclic bending test: a) Force vs. stroke curve; b) springback geometry

In both cases, the error of the predicted force before unloading is reduced to less than 10 %. As a result the calculated geometry after springback stands in good agreement with the real specimen. Despite the expectations, the parameter set identified at one load cycle (1LC) provides a slightly better prediction of the process forces as well as the springback geometry. However, it can be shown that the identification of the kinematic hardening parameters according to Chaboche et al. is possible with use of a one element simple shear model. Furthermore, the identification in just one load change is quite sufficient and the derived material parameters are able to describe a more complex deformation history.

Figure 7 shows the corresponding results of the analysis for the isotropic-kinematic hardening model according to Yoshida et al.

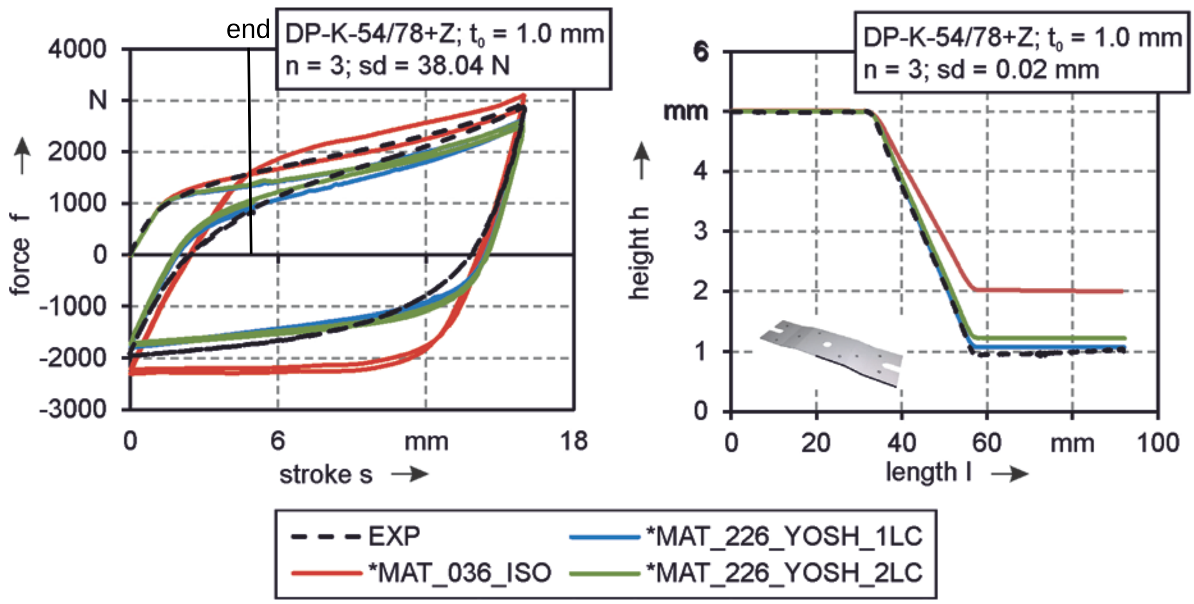


Fig.7: Validation of the Yoshida-Uemori parameters in the cyclic bending test: a) Force vs. stroke curve; b) springback geometry

Similarly to the previous observations, the use of the complex hardening model leads to a more accurate simulation of the bending process. Both the force-stroke curve and the springback geometry are mapped well. Likewise it is quite sufficient to identify the material model with just one load change.

The extended identification area brings no additional benefit in the numerical simulation of the bending process regarding a longer required time for the identification procedure.
In contrast to the Chaboche-Rousselier model, both hardening laws give a comparable prediction of the springback geometry. However, the prediction of the bending force is of a slightly inferior quality in case of the Yoshida-Uemori hardening model. Particularly under the first load application, it underestimates the bending force. This most likely results from the complete identification of the hardening parameters on the shear curve, whereas the isotropic approximation according to Hockett et al. of the previously presented model derives from uniaxial tension data. Due to the internal dependency of the hardening parameters of the Yoshida-Uemori model, it is not possible to identify an isotropic part separately. However, an approach could be a simultaneous adaption of two FEM-models on the basis of cyclic shear curves as well as uniaxial tension curves.

3 Conclusion

Planar cyclic shear tests are carried out to characterize the material behavior of DP-K54/78+Z under multiple cyclic loading. Moreover, the results of the shear tests are used to identify and analyze kinematic hardening laws pertaining to the predictability of the springback behavior during a cyclic bending test. It is shown, that an inverse parameter identification with the use of an one element shear model is applicable, whereas no influence of the two observed anisotropic yield criterions Barlat'89 and Yld2000-2d can be detected. In case of the kinematic Chaboche-Rousselier hardening formulation as well as the isotropic-kinematic Yoshida-Uemori model, the identification on only one load cycle is sufficient to predict the . This is also validated by a numerical springback prediction of a cyclic bending test, where both models enhance the numerical prediction quality with respect to a conventional isotropic approach. Contrary to the higher complexity of the isotropic-kinematic Yoshida-Uemori model and its more extensive identification procedure, no significant benefit can be achieved in comparison to the Chaboche-Rousselier model regarding the results of the numerical springback analysis.

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