

Improved Mapping of Yield Locus Distortion through a Strain-Dependent Calibration of the Barlat Yld2000-2d Yield Criterion

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Abstract. Accurate modeling of the real material behavior is fundamental to improve the accuracy of the finite element analysis (FEA) of sheet metal forming processes. Classical material models such as Hill'48 or Barlat Yld2000-2d do not consider the material behavior under plane strain and shear, even though these states are the primary cause of failures observed in sheet metal forming. Moreover, yield criteria are conventionally calibrated at the onset of plastic deformation to determine the initial yield locus. Isotropic hardening is subsequently assumed, based on the flow curve under uniaxial tension. However, some modern sheet metals exhibit a pronounced distortional hardening behavior, which cannot be sufficiently mapped by the conventional modeling strategy. Hence, this contribution aims to improve the mapping of the yield locus distortion by considering the plane strain and shear stress states and by performing the parameter calibration at higher plastic strains. Hereby, the yield locus exponent of the Barlat Yld2000-2d is adapted in order to accurately map the material behavior under plane strain or shear. Moreover, the influence of a strain-dependent calibration of the yield locus on the mapping accuracy is investigated. Two materials, AA5182 and DP600, are being examined. It is observed that the consideration of the plane strain state leads to a reduction of the yield locus exponent while the consideration of the shear stress state is accompanied with an increase of the yield locus exponent.

Introduction

Over the past few decades, FEA has become an indispensable tool for designing and improving sheet metal forming processes. Numerical simulations significantly reduce development time and costs in industrial manufacturing by predicting stresses, sheet thickness distributions and potential failure zones. Therefore, the mapping accuracy of forming simulations is essential and depends on the boundary and contact conditions, as well as the material model. In particular, the chosen yield criterion has a significant impact on numerical prediction accuracy. Increasing computing power and improved capabilities in material characterization enable the use of advanced material models. Compared to classical yield criteria, advanced models provide a better mapping of real material behavior. Nevertheless, modern yield criteria require a large number of input parameters, which leads to an increase in characterization effort and longer computing times. For this reason, classical material models, such as Hill'48 or Barlat Yld2000-2d [1], are still widely used. These yield criteria have the disadvantage of not considering complex load conditions, such as plane strain or shear stress.

In sheet metal forming, both mentioned states can result in failure. Under plane strain conditions, the forming limit potential is at minimum. This can be explained by the material flowing solely from the thickness direction, resulting in early necking of the material [2]. Particularly in deep drawing, plane strain conditions lead to localized necking in the transition area between the bottom and skirt of a deep drawn part, which can cause bottom fractures. According to Xavier et al. [3], more than 80 % of all failures in formed automotive components occur under near-plane strain conditions. Although pure shear does not cause thinning of the sheet, component failure can occur under shear conditions, notably for dual-phase steels [4]. Shear-induced failure can be observed in bending operations [5] and in deep drawing processes in the transition region between the flange and skirt [6]. In summary, the plane strain and shear stress states both account for a significant proportion of

material failure in sheet metal forming processes. Consequently, accurate consideration of the material behavior in these states is highly relevant. However, in the classical yield criterion Barlat Yld2000-2d [1], the material behavior under plane strain or shear is not considered in the calibration process. Rather, it is defined by two grid points and the shape of the yield locus respectively. As a result, the mapping of the aforementioned states depends on the eight input parameters of the Yld2000-2d and the choice of the yield locus exponent m , which is heuristically selected based on values found in the literature. In the case of face-centered cubic (fcc) materials, a value of $m = 8$ is recommended, while for body-centered cubic (bcc) metals, a value of $m = 6$ is usually chosen [7].

Another challenge for the conventional Yld2000-2d material model is the hardening behavior of certain modern materials. Conventionally, yield criteria are calibrated at the onset of plastic deformation to determine the initial yield locus. Isotropic hardening is then assumed, based on the flow curve under uniaxial tension. However, it is not possible to accurately map the anisotropic or distortional hardening behavior of modern materials with this conventional modeling strategy. To overcome this challenge, Wang et al. [8] used an approach in which the anisotropy coefficients α_1 to α_8 of the Yld2000-2d are varied as a function of plastic strain using sixth-degree polynomial functions. By comparing the resulting yield locus with data points, determined in a biaxial tensile test with cruciform specimen and based on a deep drawing simulation of a cylindrical cup, it was possible to achieve a higher mapping accuracy compared to the conventional Yld2000-2d. To consider the evolution of the Lankford coefficient, Küsters and Brosius [9] replaced the yield locus exponent with a strain-dependent Bézier function. Furthermore, Rentz and Merklein [10] adapted the yield locus exponent of the Yld2000-2d yield criterion to accurately map the material behavior under plane strain or shear. This approach improved the mapping accuracy of a deep drawing process. However, this method is limited to a fixed plastic strain.

Accurate mapping of the material behavior under plane strain and shear is important for improving failure prediction. Thus, this study investigates a strain-dependent calibration of the Yld2000-2d yield criterion, whereby either the plane strain or shear stress state is considered by adapting the yield locus exponent. Furthermore, the dependence of the yield locus exponent of the plastic strain is examined.

Methodical Approach

In this contribution, the two commonly used materials AA5182-O and DP600, with a nominal sheet thickness of $t_0 = 1.0$ mm are used. The naturally hard aluminum alloy AA5182 offers a good corrosion resistance and weldability. The combination of a high strength and good formability makes the aluminum alloy suited for cold forming. AA5182 is often used for car body parts and bumpers. The dual-phase steel DP600 shows a very high strength combined with a good formability due to its specially developed microstructure. These properties make this steel grade particularly suitable for manufacturing of car body parts that require high energy absorption in the event of an accident. DP600 is consequently ideal for door reinforcements and safety cells.

Identifying the parameters of the conventional Barlat Yld2000-2d yield criterion requires the characterization of two stress states. The hardening behavior under uniaxial tension and the Lankford coefficients are characterized in the tensile test according to DIN EN ISO 6892-1. Thereby, tensile specimens are tested in, diagonal to and transverse to the rolling direction. The flow behavior under equi-biaxial tension is identified in the hydraulic bulge test according to DIN EN ISO 16808. Moreover, the strain-dependent evolution of the biaxial anisotropy r_b is determined in the layer compression test according to Lenzen and Merklein [11]. The specimen stack is compressed by 50 % of its initial height. To adapt the Yld2000-2d yield criterion, the principal stress components under plane strain and shear need to be classified. Therefore, hydraulic bulge tests with an elliptical die are conducted according to [12] to characterize the material behavior under near plane strain conditions. Additionally, shear tests according to [13] are carried out. For all characterization tests, the equivalent strain rate of 0.0040 1/s for the dual-phase steel according to SEP 1240 and the equivalent strain rate of 0.0067 1/s for the aluminum alloy according to VDA 239-300 is selected.

One challenge of the commonly used Yld2000-2d yield criterion is that the material behavior under plane strain or shear condition cannot be accurately mapped, as these are not directly implemented in

the calibration process. Rather, these states are obtained by interpolation between two grid points respectively, which causes a deviation from the actual material behavior under plane strain or shear. However, the yield locus exponent m affects the shape of the modeled yield locus. The plane strain area is particularly sensitive to this, whereby a change in the geometry of the yield locus also occurs in the shear area. Consequently, the yield locus exponent is adapted in order to integrate the stress point of the plane strain state or the shear stress point respectively. The extension of the Yld2000-2d material model is conducted in Matlab 2023 according to [10]. However, the identification of the yield loci is not limited to a fixed equivalent plastic strain of $\varepsilon_{pl,eq} = 0.05$. In this contribution, the parameter calibration is performed within the range covered by the experimental data with a step size of $\Delta\varepsilon_{pl,eq} = 0.025$. Figure 1 shows the approach to consider further material data, such as the shear stress, in the Yld2000-2d yield criterion.

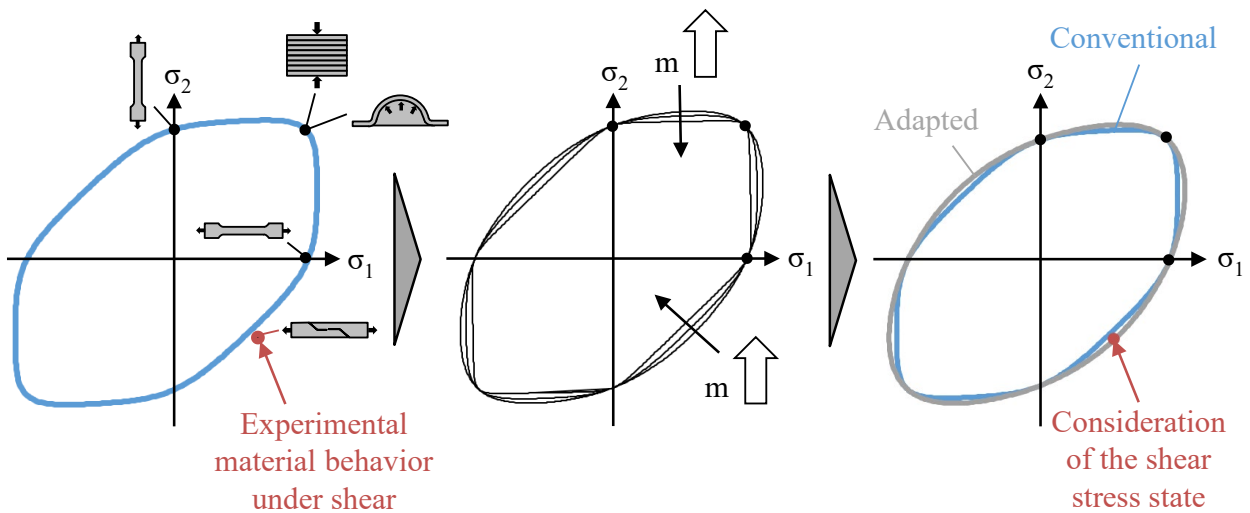


Fig. 1. Approach to the extension of the Yld2000-2d with further material information by varying the yield locus exponent m .

Material Characterization

As described above, different characterization tests are conducted to investigate the hardening behavior of the two materials AA5182 and DP600. In Figure 2, the flow behavior under uniaxial tension in dependence of the rolling direction can be observed.

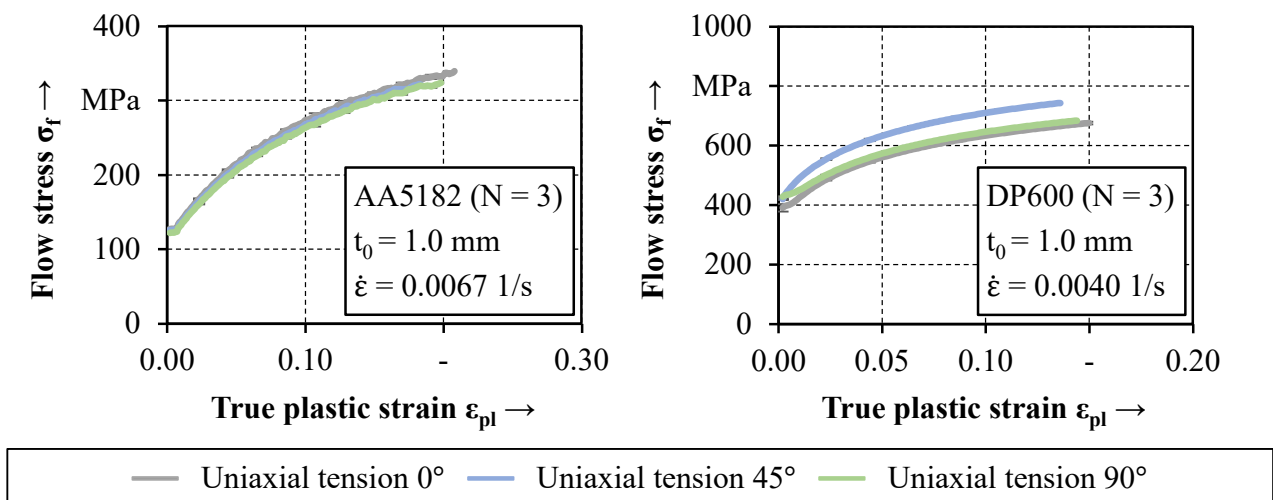


Fig. 2. Flow curves under uniaxial tension for AA5182 and DP600.

To guarantee statistical reliability, three specimens ($N = 3$) are tested for each rolling direction. For AA5182, the flow curves are on a similar level. Therefore, the aluminum alloy exhibits a pronounced isotropic material behavior under uniaxial tension. For DP600, the yield stresses under a load diagonal and transverse to the rolling direction, are comparable, amounting to 419.9 MPa and 427.7 MPa, whereas the yield stress in rolling direction is significantly lower at 390.9 MPa. However, the dual-phase steel shows a higher work hardening potential at 45° to the rolling direction compared to 0° and 90° . Hence, anisotropic hardening can be identified for DP600 in case of uniaxial tensile loading.

Moreover, to ensure the comparison of the flow behavior under different strain and stress states, the calculation of the von Mises equivalent plastic strain and stresses are necessary. In Figure 3, the stress state-dependent equivalent flow curves for the aluminum alloy AA5182 and dual-phase steel DP600 are depicted.

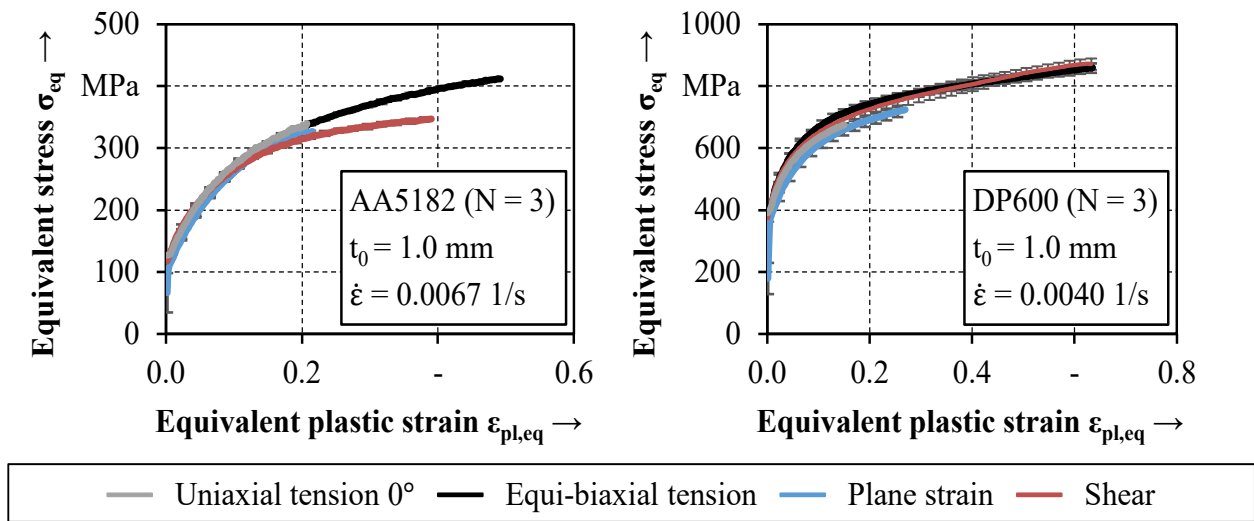


Fig. 3. Equivalent flow curves of the aluminum alloy AA5182 and the dual-phase steel DP600 in dependence of the stress state.

In case of both materials, it can be observed that the failure of the material occurs at lower equivalent plastic strains for uniaxial tension and plane strain compared to equi-biaxial tension and shear. For AA5182, isotropic hardening behavior is evident at the onset of plastic deformation. This can be observed by a similar flow behavior independent of the stress or strain state. Though, the hardening potential under shear deviates from the other strain and stress states, starting from an equivalent plastic strain of 0.1. As a consequence, the aluminum alloy exhibits anisotropic hardening behavior at higher plastic strains. In contrary, the dual-phase steel DP600 shows nearly isotropic material behavior at lower and higher strains.

It can be summarized that the aluminum alloy AA5182 shows isotropic behavior under uniaxial tension, while a slight anisotropic, stress-state dependent hardening behavior can be observed. For the dual-phase steel DP600, a pronounced anisotropic material behavior under uniaxial tension is determined. However, a stress-state dependent hardening behavior cannot be identified.

The resulting equivalent flow curves can subsequently be used in order to calibrate the conventional Yld2000-2d yield criterion. Table 1 shows the necessary parameters in order to calculate the yield locus using the conventional modeling strategy. Hereby, a yield locus exponent of $m = 8$ is selected for the aluminum alloy, while $m = 6$ is chosen for the dual-phase steel. For the parameter identification, an equivalent plastic strain of $\epsilon_{pl,eq} = 0.05$ is selected. This can be explained due to the incorrect determination of the radii of curvature in both hydraulic bulge tests, resulting in high standard deviations of the flow stress at low equivalent plastic strains. Consequently, the onset of plastic deformation under equi-biaxial and plane strain conditions cannot be accurately identified.

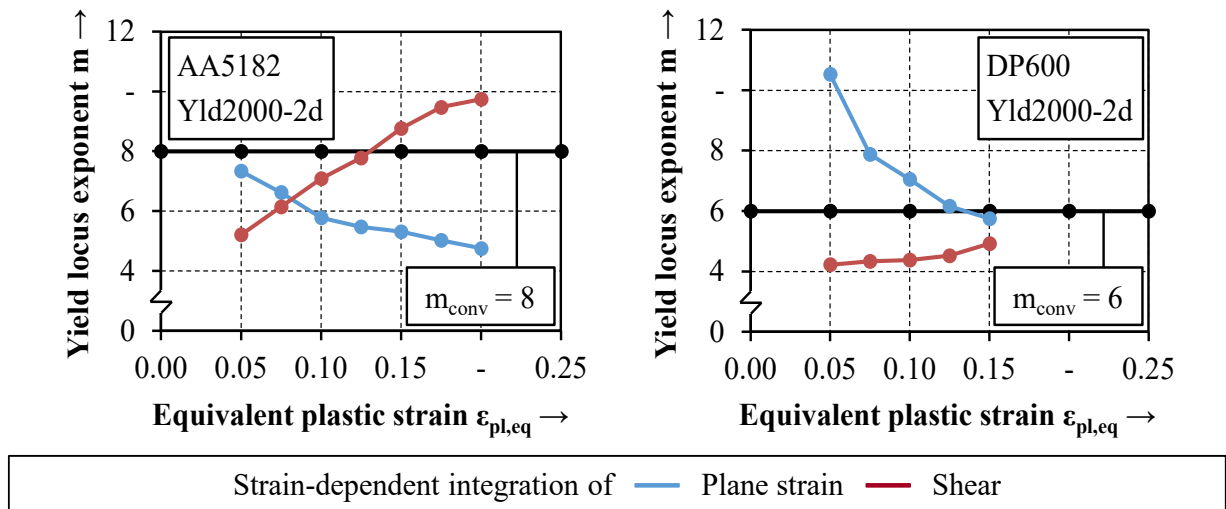
Table 1. Parameters for the conventional identification of the Yld2000-2d at an equivalent plastic strain of $\varepsilon_{pl,eq} = 0.05$.

Yld2000-2d	σ_0	σ_{45}	σ_{90}	σ_b	r_0	r_{45}	r_{90}	r_b	m_{conv}
AA5182	214.98	210.73	205.65	210.30	0.762	0.610	0.605	1.108	8
DP600	560.05	632.55	572.85	586.19	0.775	1.032	1.076	0.720	6

Yield Locus Exponent Evolution and Yield Locus Distortion

Conventionally, the parameter identification for yield criteria is performed at the onset of plastic deformation. The yield locus is then expanded isotropically based on the flow curve under uniaxial tension. However, distortionally hardening materials pose a challenge, as they cannot be accurately modeled assuming isotropic hardening. Therefore, a strain-dependent calibration of the Yld2000-2d yield criterion is investigated. Hereby, the conventional Yld2000-2d is adapted by integrating either the stress point of the plane strain state or the shear stress point respectively according to [10]. This is being achieved by adjusting the yield locus exponent m . The parameter calibration is conducted, starting from an equivalent plastic strain of $\varepsilon_{pl,eq} = 0.05$ until the upper limit of the available experimental data, with a step size of $\Delta\varepsilon_{pl,eq} = 0.025$.

In Figure 4, the strain-dependent evolution of the yield locus exponent for the investigated aluminum alloy AA5182 and dual-phase steel DP600 is depicted.

**Fig. 4.** Strain-dependent evolution of the yield locus exponent.

It should be noted that the parameter identification for both materials is limited to the achieved equivalent plastic strains under uniaxial tension. Due to that, the upper limit for the aluminum alloy is at an equivalent plastic strain $\varepsilon_{pl,eq} = 0.20$, while the identification is limited to $\varepsilon_{pl,eq} = 0.15$ in case of the dual-phase steel. For both materials, it can be identified that a strain-dependent consideration of the plane strain state leads to a reduction of the yield locus exponent m , which leads to a rounder yield locus geometry. This is due to a comparable hardening potential under equi-biaxial and plane strain conditions, which results in a rounder shape of the yield locus in the biaxial tension area. Considering the shear stress state in the Yld2000-2d yield criterion leads to an increase of the yield locus exponent in dependence of the equivalent plastic strain, which is accompanied with an increasing flattening of the corresponding yield locus. This can be explained by the lower work hardening potential under shear conditions, which is more pronounced for the aluminum alloy. Consequently, the yield locus exponent increases to a greater extent for the aluminum alloy than for the dual-phase steel.

The adapted strain-dependent yield loci can be calculated, using the determined material parameters in Figure 3 and the respective yield locus exponents. For a better overview, Figure 5 only considers the yield loci with a step size of $\Delta\varepsilon_{pl,eq} = 0.05$.

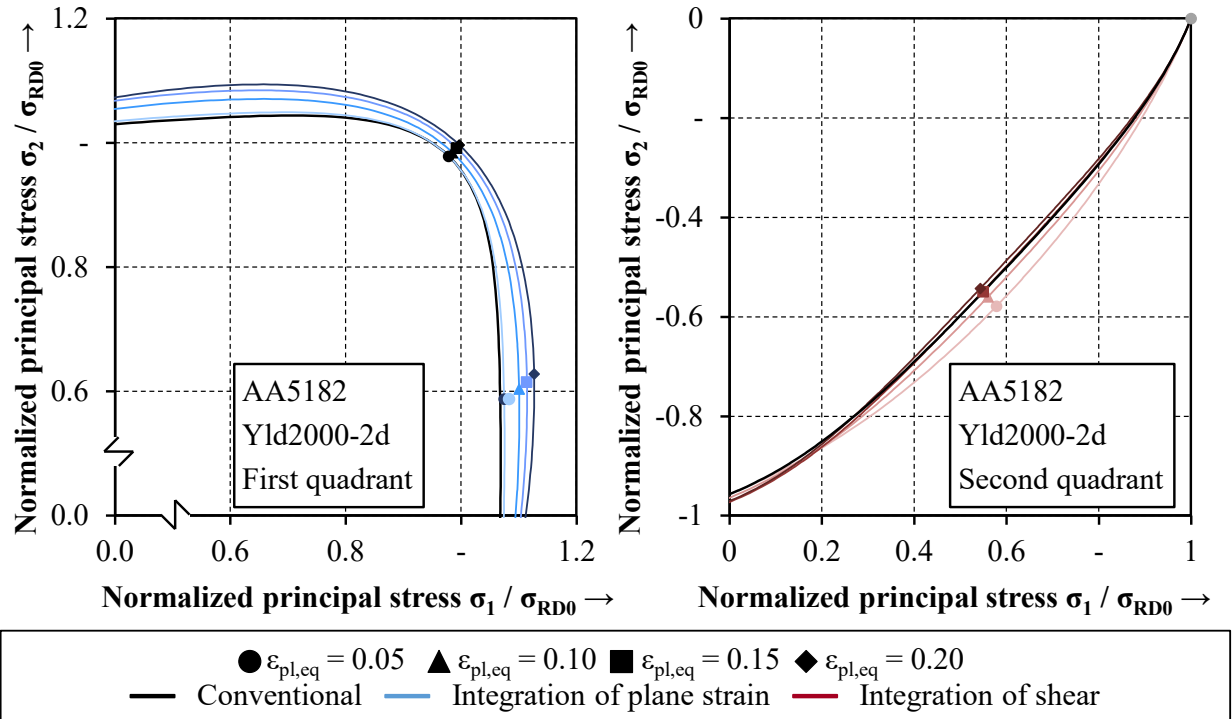


Fig. 5. Yield locus distortion for the aluminum alloy AA5182.

The black yield locus represents the common modeling strategy with a conventional choice of the yield locus exponent of $m = 8$ for aluminum alloys. Assuming isotropic hardening of the material, the normalized yield locus remains unchanged in case of plastic deformation. In the left diagram of Figure 5, the conventional yield locus and the adapted yield locus determined at an equivalent plastic strain of $\varepsilon_{pl,eq} = 0.05$ are in good agreement. However, it can be observed that an increasing plastic strain leads to a distortion of the yield locus when considering the plane strain state in the Yld2000-2d yield criterion. Using the conventional approach leads to premature reaching of the forming limit due to the deviation between numerically calculated and real material behavior. Hence, the conventional modeling strategy is only able to accurately map the beginning of plastic deformation under plane strain conditions in case of the aluminum alloy. A contrary result is observed in the right diagram of Figure 5. Hereby, the onset of plastic deformation under shear conditions cannot be mapped precisely with the conventional modeling strategy. Nevertheless, the shape of the conventionally identified yield locus and the yield loci determined at higher plastic strains ($\varepsilon_{pl,eq} \geq 0.10$) are similar. Therefore, the conventional modeling strategy is only suitable for considering the shear stress state at higher plastic strains for AA5182.

Similar observations can be concluded for the dual-phase steel DP600. As can be seen in the left diagram of Figure 6, the conventional modeling strategy overestimates the onset of yielding under plane strain conditions. This influences the failure prediction accuracy once more. Though, the yield loci calculated at higher plastic strains ($\varepsilon_{pl,eq} \geq 0.10$) align well with the conventionally identified yield locus. As a result, the conventional modeling strategy cannot map the onset of yielding but can map the hardening behavior under plane strain conditions for the dual-phase steel. Considering the shear stress state, the conventionally identified yield locus has a similar curve shape compared to all of the adapted yield loci. Thus, the Yld2000-2d yield criterion accurately maps the overall material behavior of the dual-phase steel under shear conditions.

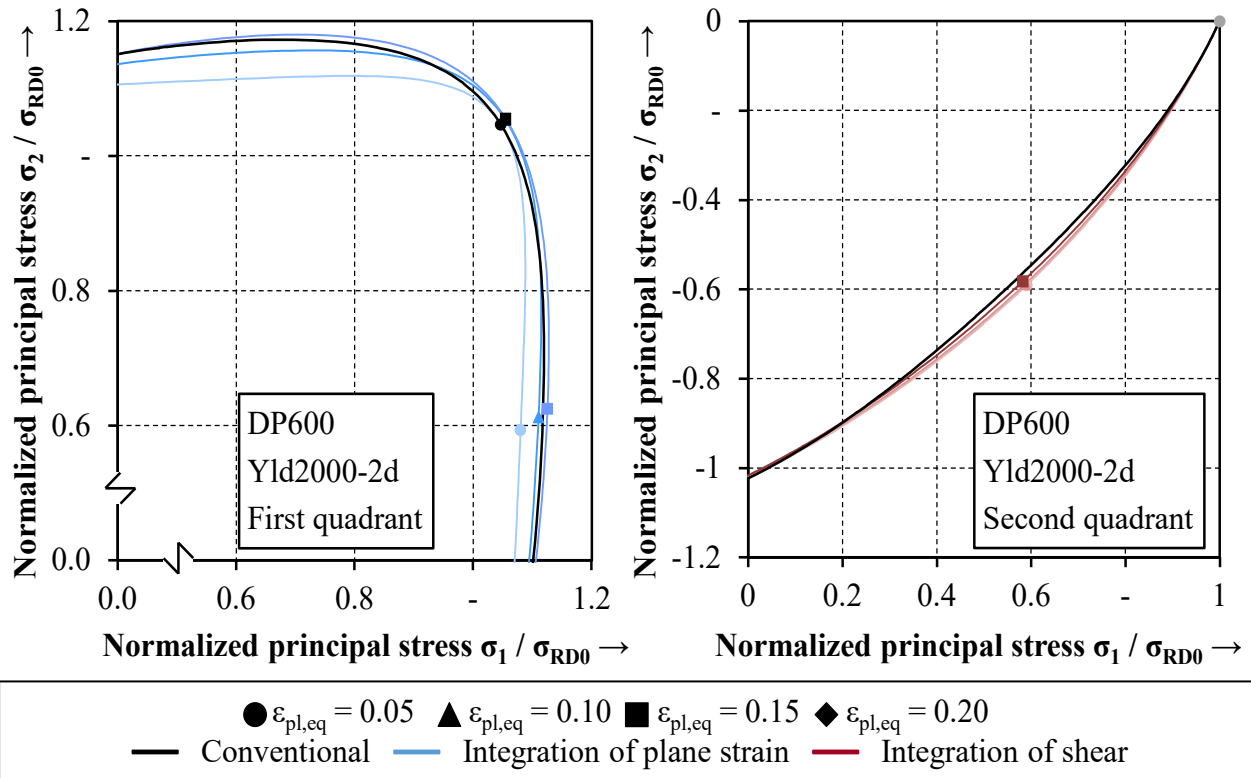


Fig. 6. Yield locus distortion for the dual-phase steel DP600.

Consequently, the following Table 2 summarizes the suitability of the conventionally identified Yld2000-2d yield criterion for the two investigated materials. With exception of the shear stress state in case of the DP600, the distortional hardening behavior is not mapped accurately with the conventional modeling strategy. Using the conventional yield criterion leads to a deviation between the modeled and real material behavior because the overall material behavior under plane strain or shear is not mapped precisely. Due to that, enhanced modeling strategies are necessary to implement the shown dependence of the yield locus exponent of the plastic strain to improve numerical mapping accuracy. Therefore, future works will focus on this aspect.

Table 2. Suitability of the conventionally identified Yld2000-2d for modeling the material behavior.

Material	Consideration of plane strain		Consideration of shear	
	Onset of yielding	High plastic strains	Onset of yielding	High plastic strains
AA5182	+	-	-	+
DP600	-	+	+	+

Summary and Outlook

Due to the relevance of the plane strain and shear stress states in sheet metal forming processes, a consideration of the mentioned states in the yield criterion is desirable. The commonly used Barlat Yld2000-2d yield criterion offers the possibility of modeling the anisotropic material behavior of modern materials. Adjusting the yield locus exponent allows the stress point of the plane strain or shear stress state to be directly integrated into the yield locus, respectively. Within this contribution, a strain dependent calibration of the Yld2000-2d yield criterion is investigated in order to improve the mapping of the distortional hardening behavior of modern materials. For both materials, it is observed that a strain-dependent consideration of the plane strain state leads to a reduction of the

yield locus exponent, while a strain-dependent integration of the shear stress state is accompanied with an increase of the yield locus exponent. Additionally, the use of a conventional modeling strategy results in a deviation of the modeled and real material behavior with the exception of the shear stress state in case of the DP600. The reason for this is, that the overall material behavior under plane strain or shear is not sufficiently mapped. In future works, the optimal equivalent plastic strain should be identified, at which the parameter identification leads to the most accurate numerical results. Moreover, the strain-dependent calibration of the Yld2000-2d yield criterion should be implemented into a user-defined subroutine and subsequently validated in a deep drawing process of cross-die samples in comparison to the conventional and adapted modeling strategy.

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References

- [1] F. Barlat, J.C. Brem, J.W. Yoon, K. Chung, R.E. Dick, D.J. Lege, F. Pourboghra, S.-H. Choi and E. Chu, Plane stress yield function for aluminum alloy sheets—part 1: theory, *International Journal of Plasticity* 19(2003)9, p. 1297–1319.
- [2] Y. Hou, K. Du, A.A. El-Aty, M.-G. Lee, J. Min, Plastic anisotropy of sheet metals under plane strain loading: A novel non-associated constitutive model based on fourth-order polynomial functions, *Materials & Design* 223(2022), 111187.
- [3] M.D. Xavier, R.L. Plaut and C.G. Schön, Uniaxial Near Plane Strain Tensile Tests Applied to the Determination of the FLC Formability Parameter, *Materials Research* 17(2014)4, p. 982-986.
- [4] J.H. Kim, J.H. Sung, K. Piao and R.H. Wagoner, The shear fracture of dual-phase steel, *International Journal of Plasticity* 27(2011)10, p. 1658-1676.
- [5] A.W. Hudgins, D.K. Matlock, J.G. Speer and C.J. Van Tyne, Predicting instability at die radii in advanced high strength steels, *Journal of Materials Processing Technology* 210(2010)5, p. 741-750.
- [6] B.A. Behrens, C. Bonk and I. Peshekhodov, On modelling of shear fracture in deep drawing of a high-strength dual-phase sheet steel, *Journal of Physics: Conference Series* 896(2017), 012125.
- [7] J.W. Yoon, F. Barlat, R.E. Dick, K. Chung and T.J. Kang, Plane stress yield function for aluminum alloy sheets—part II: FE formulation and its implementation, *International Journal of Plasticity* 20(2004)3, p. 495–522.
- [8] H. Wang, M. Wan, X. Wu and Y. Yan, The equivalent plastic strain-dependent Yld2000-2d yield function and the experimental verification. *Computational Materials Science* 47(2009)1, p.12-22.
- [9] N. Küsters and A. Brosius, An adapted yield criterion for the evolution of subsequent yield surfaces. *Journal of Physics: Conference Series* 896(2017), 012020.
- [10] M. Rentz and M. Merklein, Improvement of material modeling by considering the plane strain and shear stress state in the Yld2000-2d yield criterion, *Journal of Physics: Conference Series* 3104(2025), 012004.

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- [11] M. Lenzen and M. Merklein, Determination of strain dependent anisotropy in layer compression tests and resulting influence on the yield locus modelling, In NUMIFORM 2019: The 13th International Conference on Numerical Methods in Industrial Forming Processes, 2019.
- [12] M. Lenzen and M. Merklein, Improvement of Numerical Modelling Considering Plane Strain Material Characterization with an Elliptic Hydraulic Bulge Test, *Journal of Manufacturing and Materials Processing* 2(2018)1, 6.
- [13] M. Merklein and M. Biasutti, Forward and Reverse Simple Shear Test Experiments for Material Modeling in Forming Simulations, in: G. Hirt and A.E. Tekkaya, *Proceedings of the 10th International Conference on Technology of Plasticity, ICTP 2011*, p. 702-707.