Yield Locus Exponent Modelling of Packaging Steel for an Optimized Simulation of Limited Dome Height Experiments

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In packaging steel forming processes, conditions in-between plane strain and biaxial tension are mostly relevant as they lead to failure in deep drawing applications and characterize e.g. the process of the rivet forming in easy-open end applications. To receive precise simulation results in finite element analysis, it is important to consider an accurate modelling of the yield locus in this area. Complex anisotropic yield functions like e.g. Yld2000-2d which was proposed by Barlat and is implemented in LS-DYNA using keyword ***MAT_133** do not consider the characterization of this area and maintain an uncertain variable by the yield locus exponent. Therefore, Lenzen and Merklein [1] developed an approach to model the plane strain behaviour by means of the yield locus exponent using elliptic bulge tests. In the present work, this approach was applied to determine the yield locus exponent of the packaging steel TH415 precisely in order to simulate limited dome height experiments, which represent the forming state in packaging steel applications very well. For a further improvement, anisotropic behaviour in biaxial tension was considered as well. The yield exponent showed a strong influence on the simulation results of the friction induced forming ring in limited dome height experiments and the characterization of the yield exponent via elliptic bulge tests revealed great improvement to determine this parameter precisely. To implement the optimized characterization via the keyword ***MAT_133** in LS-DYNA simulations, the yield locus model was directly parametrized by the underlying α-values and the yield exponent, which were determined throughout an optimization process minimizing the residuum between experimental data and the model prediction.

1 Introduction

Research activities in the packaging food market are mainly driven by down gauging interests in order to reduce costs via weight reduction and an increasing importance of a minimized carbon footprint. To fulfill stability requirements as for example in aerosol applications, the development of higher-strength packaging steels has become an important market driver. Accelerating the process of adaption of tools on to the requirements of high-strength packaging steels in order to minimize the trial-and-error effort, finite element simulation have become an important tool in this field. The distinctive description of the plastic material behavior is mandatory to receive precise simulation results in sheet metal forming. Beside the implementation of a flow curve to describe the strain hardening in uniaxial stress state, the usage of an appropriate yield locus model is necessary to describe even the plastic anisotropic material behavior. Knieps et al. [2] already showed the specific requirements in the characterization of packaging steel and even the necessarily of an appropriate flow curve description and the selection of a complex anisotropic yield locus model became obvious. In commercial LS-DYNA code, several material models are implemented which fulfill these requirements. Table 1 gives an overview about two common material models in LS-DYNA code and the required material parameters. One of the more simple models was proposed by Hill in 1948 [3] and considers already plastic anisotropy via Lankford coefficients and is implemented by the keyword ***MAT_122** in LS-DYNA commercial code. However, there is a lack in the description of material behaviour in the stress state between biaxial tension and plane strain especially for material with Lankford coefficients smaller than one and biaxial strength greater than the uniaxial strength [4]. This lack is overcome by the even more complex anisotropic yield locus model Yld2000-2d proposed by Barlat in 2000 [5], which considers even different strength behaviour in different orientations to rolling direction and experimental biaxial data. This model can be applied in LS-DYNA code using the keyword ***MAT_133.** It is based on two linear transformations of the deviatoric stress tensor with eight free parameters $\alpha_1,\ldots,\alpha_8$ (equation 1-5). Two options are available in the LS-DYNA keyword to parametrize the yield function Yld2000-2d. On the one hand, there is the possibility to calibrate the material card by the experimental data σ_0, σ_{45}, σ_{90}, σ_{xx}, σ_{yy}, σ_{xy}, r_0, r_{45}, r_{90} and the responding α-values are calculated by LS-DYNA. On the other hand, LS-DYNA offers the possibility to parametrize the model directly by the underlying values of $\alpha_1,..,\alpha_8$.

$$\phi = \phi' + \phi'' = |X'_1 - X'_2|^a + |2X''_1 + X''_2|^a + |X''_1 + 2X''_2|^a \tag{1}$$

$$\begin{pmatrix} X'_{11} \\ X'_{22} \\ X'_{12} \end{pmatrix} = \begin{pmatrix} C'_{11} & C'_{12} & 0 \\ C'_{21} & C'_{22} & 0 \\ 0 & 0 & C'_{66} \end{pmatrix} \begin{pmatrix} s_{11} \\ s_{22} \\ s_{12} \end{pmatrix} \quad \begin{pmatrix} X''_{11} \\ X''_{22} \\ X''_{12} \end{pmatrix} = \begin{pmatrix} C''_{11} & C''_{12} & 0 \\ C''_{21} & C''_{22} & 0 \\ 0 & 0 & C''_{66} \end{pmatrix} \begin{pmatrix} s_{11} \\ s_{22} \\ s_{12} \end{pmatrix} \tag{2}$$

$$X' = C'.s = C'.T.\sigma = L'.\sigma \qquad X'' = C''.s = C''.T.\sigma = L''.\sigma \tag{3}$$

$$T = \begin{pmatrix} 2/3 & -1/3 & 0 \\ -1/3 & 2/3 & 0 \\ 0 & 0 & 1 \end{pmatrix} \tag{4}$$

$$\begin{pmatrix} L'_{11} \\ L'_{12} \\ L'_{21} \\ L'_{22} \\ L'_{66} \end{pmatrix} = \frac{1}{3} \begin{pmatrix} 2 & 0 & 0 \\ -1 & 0 & 0 \\ 0 & -1 & 0 \\ 0 & 2 & 0 \\ 0 & 0 & 3 \end{pmatrix} \begin{pmatrix} \alpha_1 \\ \alpha_2 \\ \alpha_7 \end{pmatrix} \quad \begin{pmatrix} L''_{11} \\ L''_{12} \\ L''_{21} \\ L''_{22} \\ L''_{66} \end{pmatrix} = \frac{1}{9} \begin{pmatrix} -2 & 2 & 8 & -2 & 0 \\ 1 & -4 & -4 & 4 & 0 \\ 4 & -4 & -4 & 1 & 0 \\ -2 & 8 & 2 & -2 & 0 \\ 0 & 0 & 0 & 0 & 9 \end{pmatrix} \begin{pmatrix} \alpha_3 \\ \alpha_4 \\ \alpha_5 \\ \alpha_6 \\ \alpha_8 \end{pmatrix} \tag{5}$$

However, in the standard procedure to calibrate this model as proposed by Barlat et al. [5], it is not possible to model the area of plain strain precisely and there is still one free parameter remaining by the yield exponent, which is standardized set to six for ferritic steel [4]. Lenzen and Merklein [1] used this fact to optimize the Yld2002-2d yield exponent with elliptic bulge tests receiving a much more precise modeling of the plane strain forming behaviour demonstrated in cruciform cup drawing experiments for materials in a thickness of one millimeter.
To measure the biaxial anisotropy coefficient Lăzărescu et al. [6] proposed the hydraulic bulge test in 2013. Pham et al. [7] applied this method in 2016 to characterize the plastic behaviour of aluminium.
However, even for thin packaging steel sheets the demand of a precise plane strain modelling is relevant and not investigated yet. In this context, Moldovan [8] demonstrated already the need to determine the yield locus exponent of the yield locus model Yld2000-2d precisely in order to obtain precise results by simulating limited dome height experiments. These experiments are well suited to represent the forming conditions in applications like the rivet forming in easy-open end forming processes. In addition, Knieps et al. [2] demonstrated the suitability of this experiment for the requirements of packaging steel.
Thus, aim of the present study was to apply the approach of Lenzen et al. [1] on the requirements of packaging steel to simulate limited dome height experiments more precisely. To extend this method, biaxial anisotropy coefficients were considered, as well.

Model	Material no.	σ_0	σ_{45}	σ_{90}	r_0	r_{45}	r_{90}	σ_b	r_b
Hill'48	***MAT_122**	x	-	-	x	x	x	-	-
Yld2000-2d	***MAT_133**	x	x	x	x	x	x	x	x

Table 1: Commonly used material models for forming simulation available in LS-DYNA

2 Material and methods

To model the yield locus of packaging steel in the region of plane strain and biaxial tension, investigations were conducted for the packaging steel TH415. Characterized by a ferritic microstructure and a low carbon content of 0.04 wt. % , this material was continuous annealed and temper rolled down to a thickness of 0.28 mm. Due to the lacquering process in the downstream process before forming, the material has undergone another heat treatment at 200°C for 20 minutes before testing. Resulting challenges meaning slip bands appearance and low elongation for the characterization for finite element simulation were comprehensively shown by Knieps et al. [9] recently.

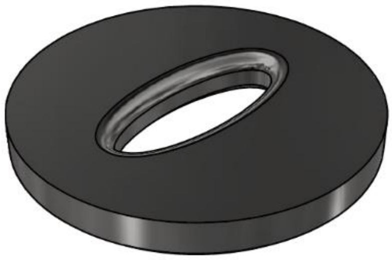
2.1 Mechanical parameters

In order to obtain the relevant parameters σ_0, σ_{45}, σ_{90}, r_0, r_{45}, r_{90} quasi-static tensile tests with a measuring length of 20 mm and a testing speed of $4 \cdot 10^{-4}$ s^{-1} were conducted. Due to the mentioned challenges arising by the low elongation in tensile tests, Lankford coefficients were determined locally on the specimen using an optical measurement system ARAMIS 12M (Fa. GOM) according to [9]. To measure the strength in biaxial tension, bulge tests were conducted using a Non-Newton Fluid (in the following referenced to as NNF) as pressure medium and a universal testing machine by Fa. Erichsen. For both, tensile tests and bulge tests the parameter evaluation was done at a plastic strain of 0.05 according to Lenzen et al. [1]. To measure the biaxial anisotropy meaning the ratio between strain in rolling direction to the strain in transverse direction (equation 6), the bulge tests was considered as proposed by Lăzărescu in 2012 [6].

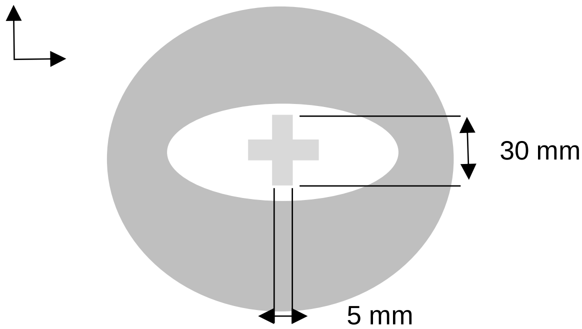
$$r_b = \frac{\varepsilon_{transverse\ direction}}{\varepsilon_{rolling\ direction}} \quad (6)$$

2.2 Elliptic bulge test

To measure the plane strain forming behaviour an elliptic die was used with an outer diameter of 100 mm and an inner diameter of 37.5 mm resulting in a ratio of 2.67 (Figure 1a). The drawing radius of the die amounts to 8 mm. Tests were conducted according to the stated bulge test procedure with a NNF at a universal testing machine. The evaluation procedure to calculate the major and minor stress by shell theory via the curvature radii was adapted to the proposal of Lenzen et al. [1] and an evaluation area with 30 mm à 5 mm was chosen as shown in Figure 1 b.



(a)



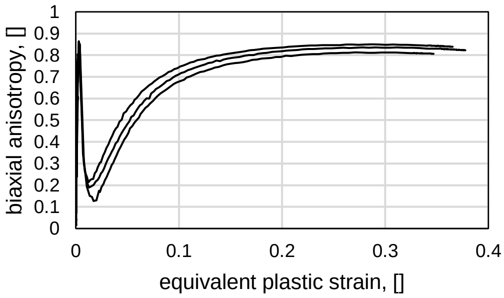
(b)

Figure 1: (a) Elliptic bulge die (b) evaluation area for curvature fitting

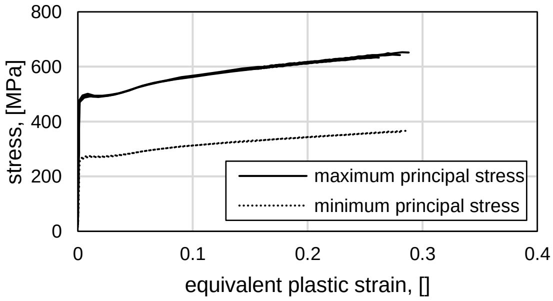
Translation and strain were measured by the digital image correlation system ARAMIS 12M which enables to measure the curvatures precisely in the described areas. The strength parameters for the yield locus modelling optimization were determined at a plastic equivalent strain of 0.05.

3 Results and parametrization of Yld2000-2d (*Mat_133)

Figure 2 shows the measured biaxial anisotropy coefficients in biaxial bulge tests. A clear anisotropy deviating from one becomes obvious. After a slight increase the anisotropy coefficients saturates at a level of around 0.8 during the testing procedure. This means a preference of the material to show more strain in rolling direction than in transverse direction under biaxial tension equivalent to equation 4 and should be considered for yield locus modelling using **`*Mat_133`**. The biaxial coefficient was averaged in between 0.2 strain and the onset of necking for three specimens, to consider the area where the biaxial anisotropy coefficient begins to saturate. The consideration of strain-dependent behaviour of the plastic anisotropy is not part of this work.



(a)



(b)

Figure 2: (a) biaxial anisotropy coefficient (b) plane strain stress curves

Figure 2 (b) presents the stress-strain curve determined out of the described elliptic bulge tests using shell theory via the two curvatures and the thickness distribution. The major and minor principal stress curves are plotted. Table 2 states the determined parameters for the yield locus determination. It becomes obvious that this packaging steel shows an anomaly with a ratio between biaxial stress and uniaxial stress greater than one and at the same time an anisotropy coefficient lower than one. Several yield locus models, e.g. Hill48, cannot describe this behaviour and thus the use of the complex model

Yld2000-2d is mandatory. As well, a higher strength in plane strain condition compared to uniaxial stress can be observed.

Model	σ_0 (MPa)	σ_{45} (MPa)	σ_{90} (MPa)	r_0	r_{45}	r_{90}	σ_b (MPa)	r_b	$\sigma_{PS,1}$ (MPa)	$\sigma_{PS,2}$ (MPa)
Yld2000-2d	452	455	485	0.78	0.89	0.83	467	0.83	498	276
Standard deviation	2.96	0.94	1.52	0.008	0.036	0.017	12.00	0.003	1.77	0.74

Table 2: Measured experimental data for yield locus calibration (n=3)

For the parametrization of the yield locus model using the underlying α-values by the keyword **`*Mat_133,`** in literature there are two different opportunities to calibrate the model. At the one hand, it is possible to solve the free parameters by a Newton iteration procedure [10]. On the other hand, it is also possible to determine the relevant parameters by a least-square algorithm, minimizing the residuum between model prediction and experimental measured data [10]. The later one will be used in this examination to determine the parameters. Therefore, equation 7 is stated summing the deviation between the model prediction and the experimental data, which was stated in Table 2. Thus, biaxial stress is given by σ_b, while σ_φ references the stress in tensile tests in different orientations to the rolling direction. In completion, σ_{PS} gives the stress state in plane strain forming condition. The anisotropy coefficients r are stated accordingly. Weighting factors w_q and w_p are chosen equivalent to 0.5. Equation 8 offers the possibility to determine the model prediction of the Lankford coefficients with F as the yield locus potential [11]. As well, the biaxial anisotropy coefficient can be predicted by equation 9. For both, the yield functions derivative is essential and was solved using a simple differential quotient by a low value of $1{\cdot}10^{-5}$ as it was proposed by Aretz et al. [10].

$$\varepsilon\,(\alpha_1,\ldots,\alpha_8,A) = w_p\left(\frac{\sigma_b-\sigma_b^{exp}}{\sigma_b^{exp}}\right)^2 + w_p\sum_{i=1}^{3}\left(\frac{\sigma_{\varphi,i}-\sigma_{\varphi,i}^{exp}}{\sigma_{\varphi,i}^{exp}}\right)^2 + w_p\left(\frac{\sigma_{PS}-\sigma_{PS}^{exp}}{\sigma_{PS}^{exp}}\right)^2 + w_q\sum_{i=1}^{3}\left(\frac{r_{\varphi,i}-r_{\varphi,i}^{exp}}{r_{\varphi,i}^{exp}}\right)^2 w_q\left(\frac{r_b-r_b^{exp}}{r_b^{exp}}\right)^2 \quad (7)$$

$$r_{\varphi,i} = \frac{sin^2\varphi\frac{\partial F}{\partial\sigma_x} - sin2\varphi\frac{\partial F}{\partial\sigma_{xy}} + cos^2\varphi\frac{\partial F}{\partial\sigma_y}}{\frac{\partial F}{\partial\sigma_x}+\frac{\partial F}{\partial\sigma_y}} \quad (8)$$

$$r_b = \frac{\frac{\partial F}{\partial\sigma_x}}{\frac{\partial F}{\partial\sigma_y}} \quad (9)$$

The optimization procedure was solved using MATLAB code with a Nelder-Mead simplex algorithm. Table 3 presents the received parameters for the yield locus optimization using elliptic bulge tests for the TH415 material. The evaluation process revealed an optimized yield exponent at a value of 7.69. In Figure 3 the yield locus is plotted for the parametrized model Yld2000-2d and for the Hill48 yield function. It becomes obvious that the more complex model Yld2000-2d gives a much more appropriate description of the experimental measured data especially in the area between plane strain and biaxial tension. As well, the variation of the yield locus exponent is suited to model this area more precisely.

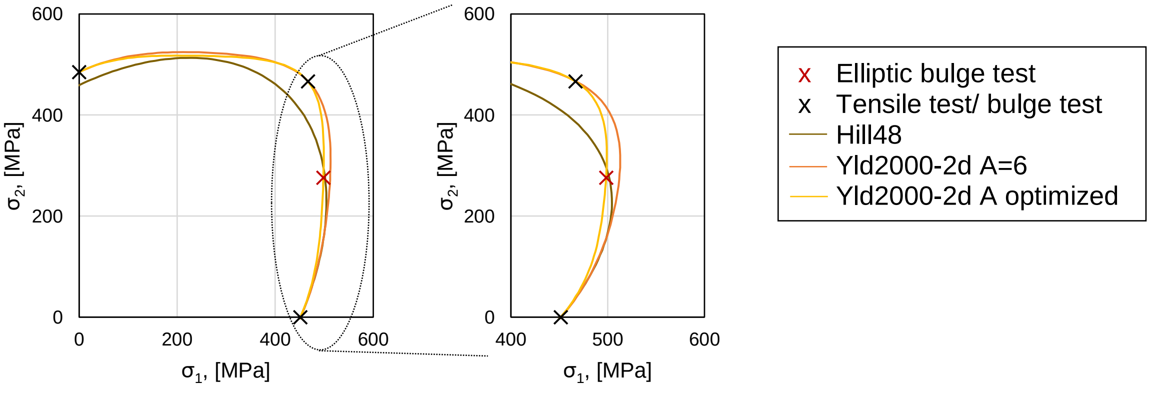


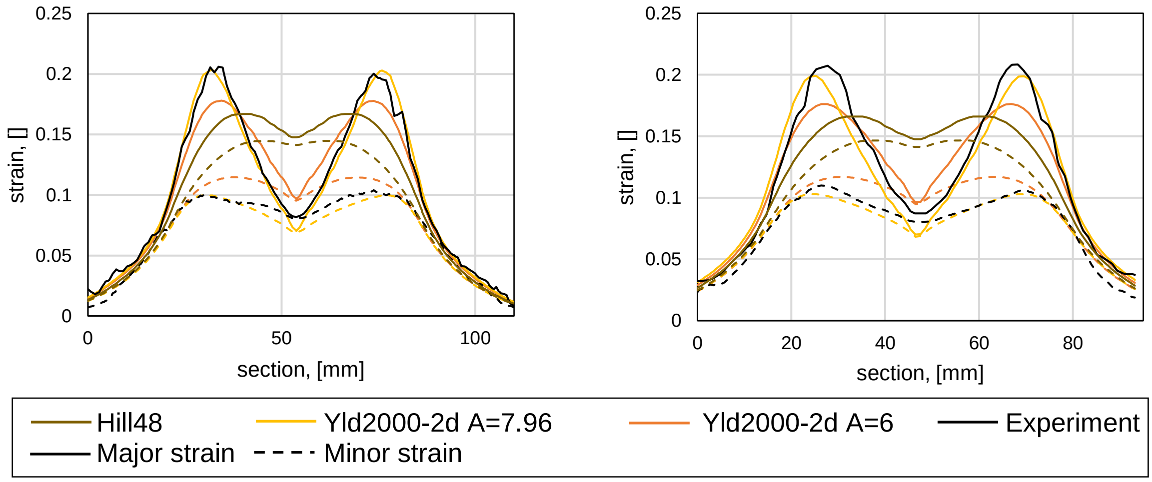
Figure 3: First quadrant of the yield locus for the packaging steel TH415

Model	α_1	α_2	α_3	α_4	α_5	α_6	α_7	α_8	A
Yld2000-2d	1.061	0.837	0.980	0.955	0.992	0.931	0.979	1.042	7.69

Table 3: Optimized Parameters for yield function Yld2000-2d

4 Validation in limited dome height experiments

To validate the results, limited dome height experiments were conducted according to Knieps et al. [2]. Therefore, a hemispherical punch with a diameter of 100 mm was used to deform a specimen, which was clamped in-between die and blankholder by a force of 160 kN. Instead of lubricant only a single layer of PET-foil was placed in-between specimen and punch to receive a complex, friction induced forming condition. To exclude surface effects, the specimens were lacquered before forming. A digital image correlation system ARAMIS 12M by Fa. GOM was used to measure the strain distribution during the forming process. This experiments represents packaging forming processes with forming conditions near to plane strain and biaxial tension as for example the rivet forming process in easy-open end applications, very well.
To simulate this experiment in order to validate the calibrated yield locus model, LS-DYNA explicit solver 12.0.0 MPP single precision was used with fully integrated shell elements, rigid dies and an edge length of one millimetre for the blank. Due to the lacquering, the forming was simulated using Coulomb friction coefficient of 0.15 and a Surface-to-Surface contact approach **`*CONTACT_FORMING_ONE_WAY_SURFACE_TO_SURFACE_ID`**. Simulations were carried out with the different yield locus models Hill48, Yld2000-2d, which was optimized by elliptic bulge tests and biaxial anisotropic parameters and Yld2000-2d with the standard yield exponent of six as it is proposed for ferritic steel. Beside the yield locus model, a proper flow curve implementation is mandatory to receive precise simulation results. Therefore, the flow curve was determined by using bulge test and tensile test extrapolated with a combined Voce and Swift hardening law according to Knieps et al. [2]. A similar procedure was already used to receive precise simulation results in simulating four-radii cups.



(a) (b)

Figure 4: Limited dome height results: section in (a) longitudinal direction (b) transverse direction

To compare experimental and simulative results, a section in longitudinal direction and a section in transversal direction through the sample in the last step before crack initiation was considered. Figure 4 displays the results for the two different sections by plotting major and minor principal strain.

Section	Hill48	Yld2000-2d A=7.96	Yld2000-2d A=6
Longitudinal direction	19 %	1 %	14 %
Transversal direction	20 %	4 %	15 %

Table 4: Deviation of different simulations to the experimental occurring maximum major strain

Comparing the results for the longitudinal direction the predicted maximum principal strain for the yield function Yld2000-2d with a yield exponent of six is about 14 % lower than experimentally observed maximum strain. Comparing the newly implemented optimization the major strain is only underestimated by about 1 %. The Hill48 yield criterion underestimates the experimental maximum major strain even by about 19 %. It becomes obvious that the implemented procedure to optimize the Yld2000-2d criterion via elliptic bulge tests and biaxial anisotropy gives the best approximation on to the experimental data. The simulation fits the experimental data very well, while for a yield exponent equal to six and Hill48 yield function significant deviations can be observed. Similar findings were carried out for the section in transversal direction. The yield locus model with an optimized yield exponent gives the best approximation of the experimental data and the maximum occurring strain deviates only by about 4 % to the experiments. With a standard yield exponent of six the simulations deviates by about 15 % from the maximum occurring experimental strain and by about 20 % for the Hill48 yield function.

5 Summary and outlook

To summarize the main findings the following conclusion can be drawn:

- The approach of Lenzen and Merklein [1] to use elliptic bulge test for plane strain characterization was successfully applied for thin packaging steels. Therefore, it was possible to determine the major and minor stress-strain hardening curve in plane strain forming condition
- The yield exponent of the yield criterion Yld2000-2d was optimized using elliptic bulge test data to determine the underlying parameters throughout a mean square error algorithm. In addition, also biaxial anisotropy was considered to get a highly precise modelling of the yield locus behaviour in the region between plane strain and biaxial tension.
- Limited dome height experiments were simulated with the newly implemented approach and the simulation accuracy showed great improvement in mapping the friction induced forming ring compared to the standard procedure with Yld2000-2d and a yield exponent of six and the yield locus model Hill48.

In addition, a parametrization workflow was proposed to determine the relevant parameter in an optimization process for the use in LS-DYNA keyword **`*Mat_133`**. In future, the suitability of this method on to the requirements of even higher-strength packaging steels should be investigated, where a significant deviation between the plane strain stress state in rolling direction and transversal to the rolling direction can be observed. Therefore, both, the data in longitudinal and transversal orientation to the rolling direction, should calibrate the model. In addition, the influence of high strain-rates as they occur in packaging forming processes are not investigated, yet.

6 References

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