Virtual modelling of forming processes in metal packaging industry

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Nowadays the finite element method is technical standard in many industry sectors such as automotive manufacturing. Thus the material behaviour for steel applications in this field is extensively developed. In packaging industry, virtual approaches in process- and product development are more the exception. Instead, the cost-intensive and time-consuming trial-and-error method is commonly used to approach the limits of the material specific formability. Packaging steel is characterised by thicknesses between 0.1 to 0.49 mm and thyssenkrupp Packaging Steel offers strengths between 180 to 750 MPa. However, with tougher process limits, especially due to continuous thickness reduction, this method has its limitations. Speaking of material saving and optimisation simulation tools are gaining increasingly importance. In contrast to the automotive industry, established approaches for material characterisation do not exist and not all norms cover that low thickness range for sheet materials. The following work gives an indication of current possibilities for material characterisation of thin steel sheet. A completed validation ensures process and product designing with available material models.

KeyWords: packaging steel, thin sheet, simulation, material characterisation

1 Introduction

Packaging steel is characterised by a very low sheet thickness realised by high cold rolling respectively temper milling degrees up to 40 %. In order to cover the various requirements of a wide product range an equally wide range of tempers is offered as seen in figure 1.

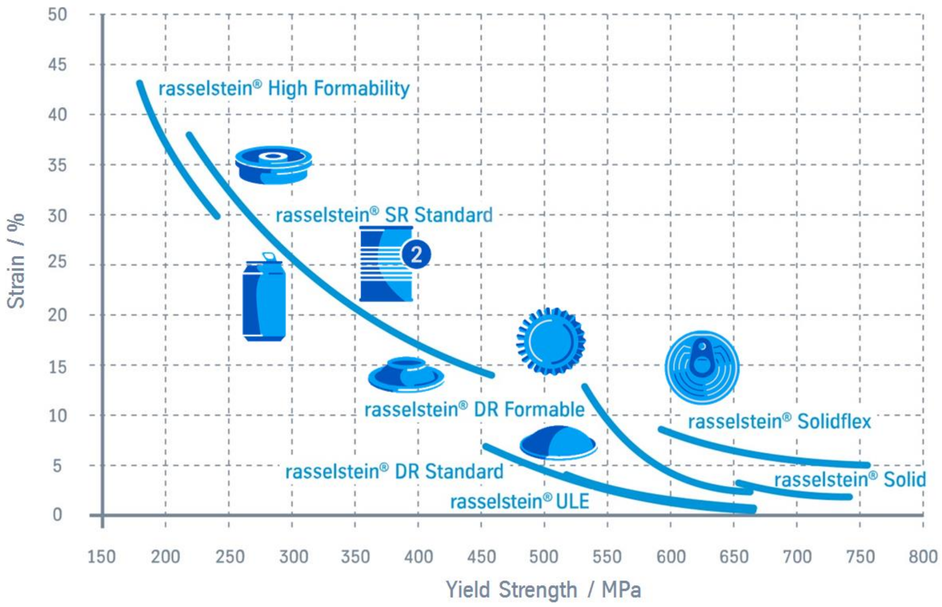

Fig.1: thyssenkrupp Packaging Steel product range and their applications

Unlike in the automotive sector packaging steel is mostly formed lacquered. It requires for certain temper the consideration of the altering processes for the complete material characterisation procedure. Another special feature is the short processing time, which can reach up to approximately 300 strokes per minute for deep drawn products [1] or approximately 1000 strokes per minutes for flat products [2]. Typical modes of failure are i.a. wrinkles and cracks during the forming processes. The

design and planning of packaging products also needs to consider following load cases. Examples for this are pressures of approximately 20 bar in aerosol cans or high axial loads on cans resulting by several stacked pallets. The validation of the stability process for such low thin sheets should as far as possible base on the forming processes. Hence, validated material cards are necessary to get accurate information about the material behaviour.
The following analysis refers to the tinned temper TS290 with a sheet thickness of 0.18 mm and yield strength of 290 MPa. Tempered soft steels, short TS, are characterised by batch annealing and e.g. used for valve discs, bodies in aerosol cans and different types of top and bottom lids.

2 Material characterisation

In industry, the most common test determining forming potential for material characterisation is the tensile test. It allows the evaluation of the mechanical characteristics and hardening behaviour. This information is necessary for a proper prediction with FEM tools. However, the test enables only relatively low strains, approximately up to 20 %, whereas industrial applications may reach much higher values. The hydraulic bulge test, which is nowadays standardised, allows the determination of the hardening behaviour at large strains [3]. The bulge stress-strain curve is transformed with a best-fit method on to the uniaxial stress state and can be extrapolated with different equations as seen in figure 2. Good experiences have been made using a linear combination of the classical functions Swift and Voce, whereby α can become greater than one [4]. In this case, the resulting flow curve by the combination is very similar to the Swift function. A comparison by the different approaches show that a simpler extrapolation method based on the tensile test does not necessarily result in an appropriate hardening behaviour.

Swift: $$\sigma = \mathrm{k} \cdot (\mathrm{b} + \varepsilon)^n \tag{1}$$

Voce: $$\sigma = \sigma_\infty + (\sigma_0 - \sigma_\infty) \cdot e^{-n\varepsilon} \tag{2}$$

Combination: $$\sigma = \alpha \cdot \mathrm{Swift} + (1 - \alpha) \cdot \mathrm{Voce} \tag{3}$$

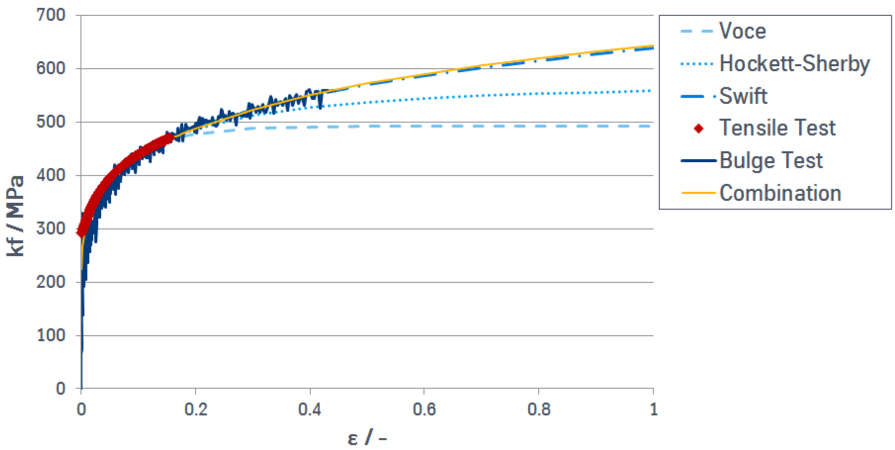

Fig.2: Different methods for flow curve extrapolation – TS290

For the description of the anisotropic material behaviour, several yield locus models exist. Table 1 shows commonly used material models for forming simulations available in LS-Dyna. The simplest is Hill'48 that needs three Lankford coefficients. In the past, the models became more complex allowing a more flexible fit to the material needs [5]. At the same time, the experimental effort increases with the need of additional parameters. However, a more complex model cannot be equated with a better model. The choice of the yield locus affects the simulative results and has to be validated.

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	-	-
Hill'90	`*MAT_243`	X	-	-	X	X	X	X	
Barlat'89	`*MAT_36`	X	-	-	X	X	X	X	-
Barlat'2000	`*MAT_133`	X	X	X	X	X	X	X	X

Table 1: Commonly used material models for forming simulation available in LS-Dyna [5]

Figure 3 shows the yield locus models from table 1 for TS290 graphically. With Barlat'2000, the user has a more flexible yield condition [6]: On the one hand, it allows meeting the stress ratio in different angles to rolling direction, here additionally 45° and 90°. On the other hand, the flow potential exponent or A-value allows influencing the shape of the yield locus. In the literature an A-value of 6 for body centred cubic materials like steel and 8 for face centred cubic materials like aluminium is recommended. An increase of the value up to 8 becomes obvious in the area of plane strain.
A first approach to validate the yield locus with the material behaviour is comparing the yield stresses from the tensile test in 0° and 90° and biaxial stress point from the bulge test. The best accordance with the measured data points for the planar stress state shows Barlat'2000. However, this method quickly reaches its limits. It is not possible to evaluate the quality for the further shape of the yield surface and to differ these two variations. To do so additional experiments like the biaxial tensile test are necessary, which causes a lot more efforts and costs [7].

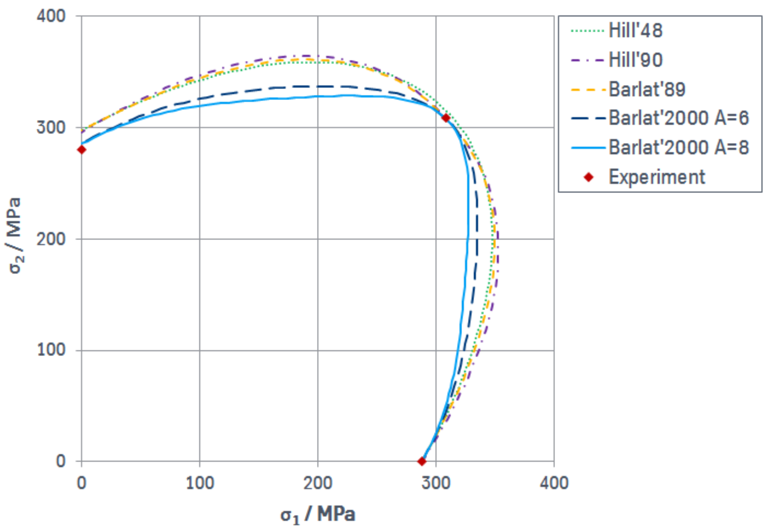

Fig.3: Yield loci available in LS-Dyna for forming simulation – TS290

3 Validation of yield locus modelling

Another option to validate the material cards is to compare simulation data with actual forming parts. For that, a set of experiments on a laboratory scale is available, which feature differentiated stress conditions based on real customer processes. In packaging industry, the mostly occurring forming steps are deep drawing and spherical shaping. Cups find themselves usually as first forming step (single-stage or multi-stage) in most of the packaging forming processes. Spherical deformations appear for example at the bottom of aerosol cans or Easy-Open-End rivets. Therefore, a deep drawn cup and the Nakajima test were chosen to represent typical parts. The forming analysis was performed offline with the optical system ARGUS by GOM.
Figure 4 illustrates the comparison between the experimental and simulated results. A distinction of the various anisotropy models is barley possible on the basis of a deep drawn cup, all show similar good results. Whereas the Nakajima test shows a significant influence of the yield locus models on the strain distribution. The experiment does not distribute a typical biaxial but a mixed plane strain deformation. The Hill models and Barlat'89 are not able to map the experimental results. For Barlat'2000 the influence of the flow potential exponent becomes obvious. The higher the A-Value, the

more it approaches a plane strain condition. On the other side, the simulation overestimates the major strain and leads to early necking, which may occur due to an inadequate modelling of the friction.

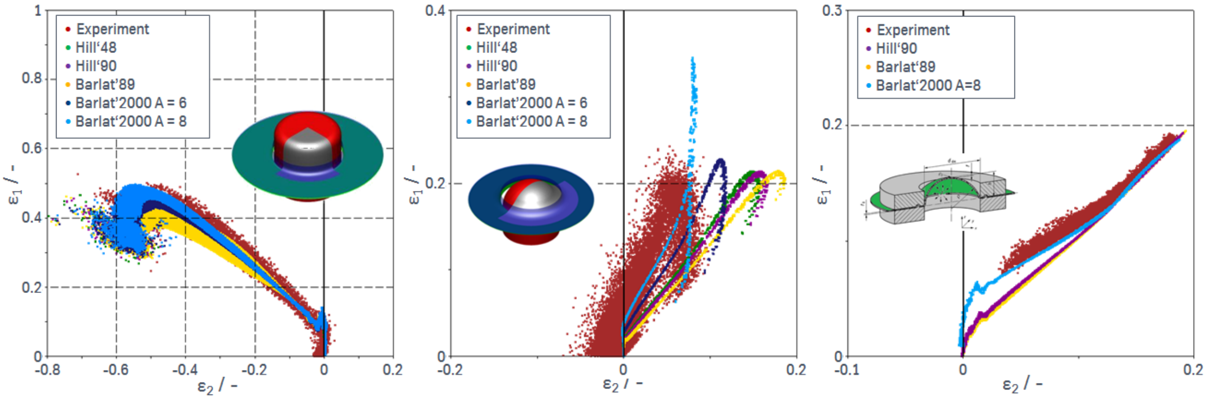

Fig.4: Influence of various yield locus models on a deep drawn cup (left), Nakajima test (middle) and hydraulic bulge test (right)

To eliminate the influence of friction the Bulge test was simulated. A comparison between the experimental parts shows the differing strain distributions. The maximum of true strain appears on the pole whereas the Nakajima test forms a ring-shaped strain maximum in some distance, as seen in figure 5. The simulation models uses the contact modelling **`*CONTACT_FORMING_ONE_WAY_SURFACE_TO_SURFACE`** with a static coefficient of friction of 0.125. Further investigations showed that a simple change of the coefficient of friction to lower and higher values does influence but do not improve the results. Different approaches to model the tribological behaviour of packaging steel should be done and are not part of this study. Moreover, an extract of the various yield loci was analysed to check their quality. The experimental results show in general a biaxial strain distribution. However, Barlat'2000 follows the outer regions of the specimen more precisely. In both cases, it predicts the material behaviour best with an A-value of 8.

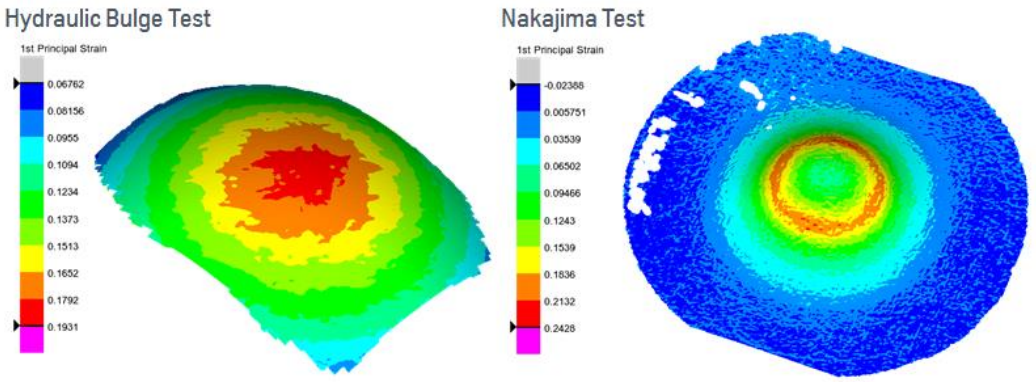

Fig.5: Experimental major strain distribution of Bulge test (left) and Nakajima test (right)

Finally, the tensile test in 0°, 45° and 90° to rolling direction and a continuous testing speed of 0.004 s^{-1} was simulated to confirm the results from chapter 2 and to check the prognosis for an additional angle to rolling direction. The results, as seen in figure 6, show deviations from the experiment for the Hill-family especially for diagonal specimens, whereas the Barlat-models match overall better. Barlat'2000 shows continuous good results for all directions except at the beginning of the stress-strain curve, which has to be improved.

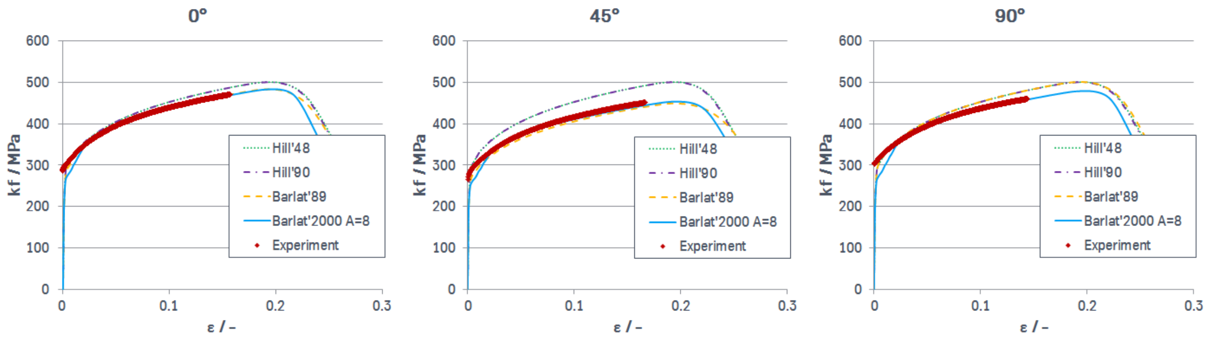

Fig.6: Influence of yield locus on tensile test for 0°/ 45°/ 90° to rolling direction

4 Influence of strain rate sensitivity

As mentioned in the beginning the stamping velocity for packaging steel applications may reach high values and hence leads to high strain rates during the forming process. For this purpose, high-speed tensile tests at strain rates of 1 s^{-1}, 10 s^{-1}, 100 s^{-1} and 250 s^{-1} have been performed [8]. For modelling the strain rate sensitivity different approaches exists. In scope of this work the Cowper-Symonds equation was chosen, which is implemented in several material models by LS-Dyna. The formula has been adapted by the factor $\frac{1}{2}$:

$$\sigma(\varepsilon_p, \dot{\varepsilon}_p) = \frac{1}{2}\sigma_Y(\varepsilon_p)\left\{1 + \left(\frac{\dot{\varepsilon}_p}{C}\right)^{\frac{1}{p}}\right\} \quad (4)$$

The left chart in figure 7, shows the comparison between the measured flow curves and the Cowper-Symonds equation, abbreviated to “CS”. The deviation is marginal for lower draw speeds and increases for high ones. The time-dependent material phenomena has been analysed for the Nakajima test. The punch velocity was set to 1 mm/s, which caused a maximum strain rate of 0.035 s^{-1} in the experimental part. Therefore, the Cowper-Symonds approach is sufficient for this study. Two different procedures for simulation modelling were used. First, high-speed flow curves based on the experimental velocities have been generated. Second, additional flow curves with strain rates between 0.008 s^{-1} and 0.15 s^{-1} have been generated to avoid a linear distribution between the data by a higher resolution in the lower strain rate area. Both approaches are presented in the right chart of figure 7, where the first is marked with “Low Resolution” and the second with “High Resolution”.

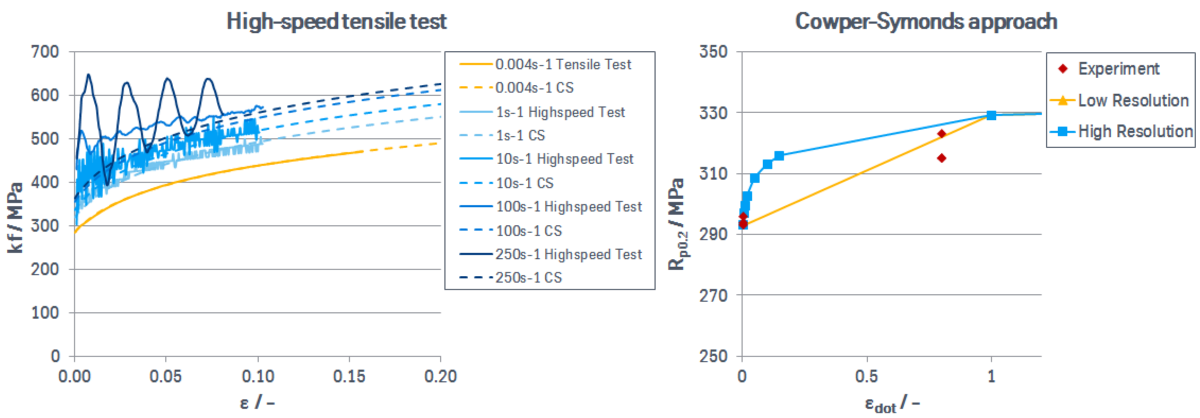

Fig.7: Strain rate modelling with Cowper-Symonds equation – TS290

The analysis is limited to the Barlat models, due to the better matches already described in chapter 3. The strain rate sensitivity has in general little effect to Barlat’89 as seen in figure 8. By contrast, Barlat’2000 with an A-value of 8 shows a clear strain rate influence and even the progression between the measured data points affects the results. A linear interpolation between the curves improves the material model little, whereas a higher resolution has a stabilising effect and leads to a good match with the experimental data. Because no significant influence of strain rate sensitivity has been observed for the deep drawn cup, the results are not discussed here.

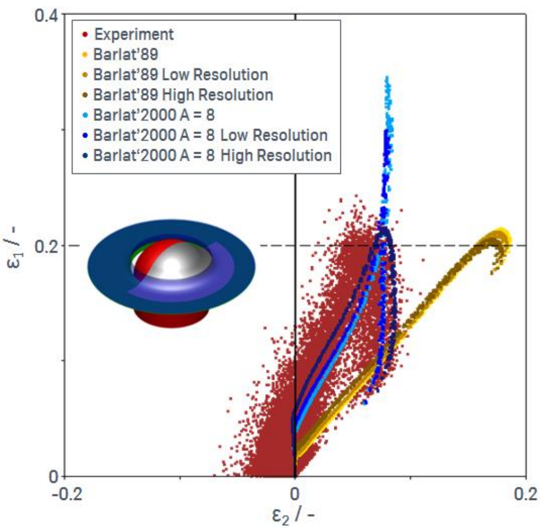

Fig.8: Influence of strain rate sensitivity for Nakajima test

5 Summary

Due to its low sheet thickness, packaging steels take a special position in the field of virtual processing. However, an increasing interest is observed due to its high potential for optimal material usage and further development of processes and designs. To meet this trend, validated material data are necessary. For this reason, a process for generating material cards for customer applications in the field of packaging steel continuous.

The statements made in this work relate to temper TS290 with 0.18 mm sheet thickness from the thyssenkrupp Packaging Steel portfolio. It shows that material characterisation and validation processes are feasible for packaging steels, whereas still need for research exists. It does not claim to give a general recommendation on the procedure. Four different yield loci were analysed and compared under different forming conditions based on real customer processes. The results confirm the conclusions already made in [5]: The higher the model flexibility the lower the deviation from the experimental data. Nevertheless, no sufficient results could be found to fit spherical deformation under the influence of friction, which may be caused by insufficient description of the tribological behaviour. Because manufacturing processes in the field of packaging steel aim short processing times, strain rate sensitivity was analysed with the Cowper-Symonds equation. The simulation model showed an explicit approach to the experimental test for Barlat'2000.

6 Literature

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