Drawing Capability of High Formable Packaging Steel: Comparison of Limiting Drawing Ratio and Forming Limit Curve

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Abstract. To assess the suitability of different packaging steels for complex deep drawing applications, nowadays, the total elongation and the Lankford coefficients in simple tensile tests are used. However, the simple use of uniaxial tensile tests is not supposed to predict the limiting drawing ratio precisely and thus the suitability for deep drawing applications. At the same time, the conduction of limiting drawing ratio experiments is extensive and requires a high testing effort. Therefore, in this work, the correlation between the forming limit curve results were compared to the results of limiting drawing ratio experiments to predict the formability of packaging steel by a much simpler criterion. At the same time, different approaches to calculate the plane strain forming limit by tensile test data were used to assess the drawing capability of packaging steel. Results revealed a strong correlation between the measured plane strain forming limit and the limiting drawing ratio at a fixed blank holder force. However, calculation methods based on tensile test data were not able to predict the drawing capability sufficiently.

Introduction

The packaging sector has developed several new steel grades over the last decades. Beside the general development of higher strength materials, also the demand of high formable steels for complex deep drawing applications is increasing. E.g., for the forming of the valve cup for aerosol tops, a high level of deformation is present and thus, there are high demands on the used material. Therefore, the application oriented material selection is crucial to receive most stable forming processes. To assess the forming capability of different steel grades, standardized quasi static-tensile tests are used nowadays in order to measure the total technical elongation. However, the fact that in complex deep drawing application much different forming conditions exist, suggests, that only the consideration of the tensile test elongation is quite an oversimplification. At the same time, the most fundamental approach to investigate the deep drawing capability in literature is the measurement of the limiting drawing ratio and the limiting drawing diagram [1]. Therefore, cups with different drawing ratio - meaning the ratio between cup and trim - and different blank holder forces are drawn. Hence, it is possible to plot the process window, where a cup without wrinkles or tear offs can be drawn. However, as this investigation requires a high experimental effort, it is not capable to conduct for all kind of different steel grades.

As well, in literature it was stated several times, that the critical forming state in deep drawing applications is found in the plane strain forming area at the punch radius [2].This is the area with the lowest level of forming before necking and leads therefore to tear offs in deep drawing applications. The maximum strain in plane strain forming condition is described in forming limit curves as Keeler introduced them [3]. In principal, different tailored specimens are deformed until failure and the onset of necking for the different forming conditions is measured. Therefore, aim of this work is to investigate, whether the plain strain specimen of the Nakajima test is able to predict the drawing capability as it was measured in limiting drawing ratio experiments for packaging steel.

At the same time, it exists a big variety of different approaches to calculate the forming limit curve. On the one hand, there are approaches like the ones presented by Swift [4] and Hill [5] to predict the forming limit by necking theory. Therefore, Hill stated that for the forming limit the sum of major

and major strain equals the hardening coefficient. On the other hand, there are more phenomenological approaches, which predict the forming limit by tensile test results. Thus, Keeler et al. presented one of the first phenomenological approaches in 1977 by using only the hardening exponent and the material thickness [6]. Fundamental basis was the assumption that the uniform strain matches the hardening coefficient as Hollomon proposed it in his hardening law. As well, Cayssials et al. developed their approach in 1998, considering hardening coefficient, strain-rate sensitivity and material thickness [7]. However, a detailed description of this model is not available in open literature, anyway. At least, Abspoel and Scholting presented their model in 2013 by correlating tensile test parameters to Nakajima tests considering higher strength-steels as well [8].

Thus, beside the above mentioned issue, in this work it was investigated, how theoretical approaches which mainly use tensile test data to determine the plane strain forming limit are able to predict the deep drawing capability as measured in limiting drawing ratio experiments.

Materials and Testing Procedure

To investigate the discussed issues, five different packaging steels were considered as they are stated in table 1. All investigated steels have a comparatively low yield strength and lie in a thickness range between 0.20 and 0.21 mm. As more complex forming operation even require more drawing capability some special steel grade have been developed to meet this demand. They are marked in the table with "HF" meaning high formable and differ mainly in the alloying composition especially for the two variants of HF245 (var1 and var2).

Table 1: Investigated packaging steels

Packaging steel	Thickness	Yield strength (as annealed)
HF200	0.20 mm	~210 MPa
HF245 var1	0.21 mm	~240 MPa
HF245 var2	0.21 mm	~240 MPa
TS275	0.20 mm	~270 MPa
TS245	0.20 mm	~250 MPa

Forming Limit Curve. The individual forming limit depending on the forming condition can be expressed by forming limit curves. They present the begin of necking in a diagram with major strain as a function of minor strain. The forming limit curve can either be determined experimentally or calculated by tensile test data.

Experimental Determination.

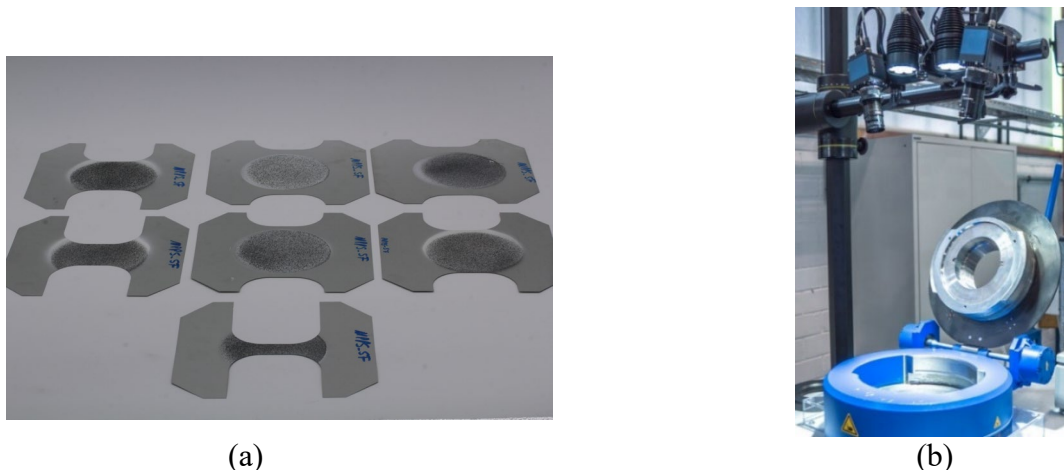(a)   (b)

Figure 1: (a) seven different tailored Nakajima specimens (b) Erichsen universal testing machine

Experimental determination of the forming limit curve was done according to Nakajima and DIN ISO12004-2:2021 [9] with a hemispheric punch and seven different tailored specimens to get forming

conditions from biaxial tension to uniaxial tension (figure 1). To exclude edge influences the specimens were milled. Test were conducted at an Erichsen Universal Testing machine with a blank holder force of 160 kN and three specimens for each geometry.

Calculation of plane strain forming limit. Beside the possibility to determine the forming limit curve by experimental effort, several calculation approaches have been established in the past. The most common ones were introduced in the first part of this work. In the following investigation, the approaches of Hill, Keeler and Abspoel will be considered to calculate the plane strain forming limit. Accordingly, Hill assumes, that the maximum forming limit for plane strain forming is equal to the hardening coefficient (eq. 3). While the approach of Keller (eq. 1) uses also the hardening exponent and in addition the material thickness, the plane strain forming limit in the Abspoel approach is only dependent on the total elongation in tensile tests with A80 specimens (eq. 2). To determine the relevant parameters quasi static tensile tests with a measuring length of 80 mm were conducted at a Zwick-Roell testing machine. To determine the hardening exponent, the evaluation was done in-between 10 % and 15 % elongation. All approaches are rate-independent and might therefore result in deviations. However, the strain-rate sensitivity, as it is known for steels, in particular has an influence on the elongation after the onset of necking [10].

Keeler: $\quad \varphi_{1,\text{plane strain}} = \ln[1+((23.3+14.13t_0)n/0.21)/100]$ $\qquad\qquad$ (1)

Abspoel: $\quad \varphi_{1,\text{plane strain}} = (0.0084\,\text{UE}_{80}+0.0017\,\text{UE}_{80}(t_0-1))$ $\qquad\qquad$ (2)

Hill: $\quad \varphi_1+\varphi_2 = n$ $\qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad\quad$ (3)

Limiting Drawing Ratio. The limiting drawing ratio experiment is the most common investigation to determine the possible operating deep drawing windows for different steel grades. It provides the information in dependency of the blank holder force and the drawing ratio whether a cup without wrinkles and tear offs can be drawn or not. Thus, it is the most application-oriented test when assessing the drawing capability of different steel grades. For the described packaging steels, tests were conducted at a Lauffer hydraulic press with a punch diameter of 69 mm and a punch radius of 5 mm. The drawing ring has a drawing gap of 0.32 mm and a drawing radius of 2.25 mm. To exclude surface influences specimens were lubricated with DOS oil. For each material different variations of drawing ratio and blank holder force were conducted.

Results

Figure 2 presents the results for the forming limit curve according to Nakajima. The biggest differences are obvious in the area of plane strain up to biaxial tension and lie in a range of about 0.05 major strain. In this area, the high-formable steels show a higher forming limit in comparison to the standard grades. The left area of the diagram reveals only slight differences in the forming limit, with the exception of the 20 mm specimen at the left edge of the diagram. In this area, the different materials also differ in the reached minor strain beside the differences in major strain.
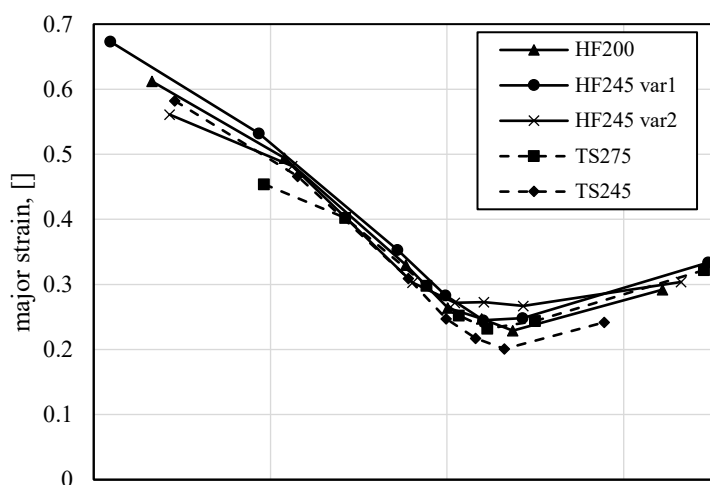
Figure 2: Forming Limit Diagram for five different packaging steels.

As well, the plane strain forming limit was calculated by different approaches which have established in literature, assuming that this forming condition is the most relevant for failure in deep drawing. Thus, figure 3 maps the calculated plane strain forming limit as a function of the measured results (n=3) for the five materials and the three different approaches. The standard deviation of the experimental measured data points lies in-between 0.003 and 0.008. The

Figure 3: Calculated plane strain necking initiation

straight line through the origin symbolizes a perfect match between calculation and measurement. The calculation based on Hill predicts much to less plane strain forming, as well as the approach of Keeler. However, the Keeler calculation provides already better results and matches the experimental results even better than the calculation by Hill. The best results offers the model by Abspoel, which is only based on the total tensile test elongation for the plane strain forming limit. The mean deviation amounts to 0.02 in comparison to 0.05 for the Hill model meaning a significant deviation compared to the standard deviation of the experimental data.
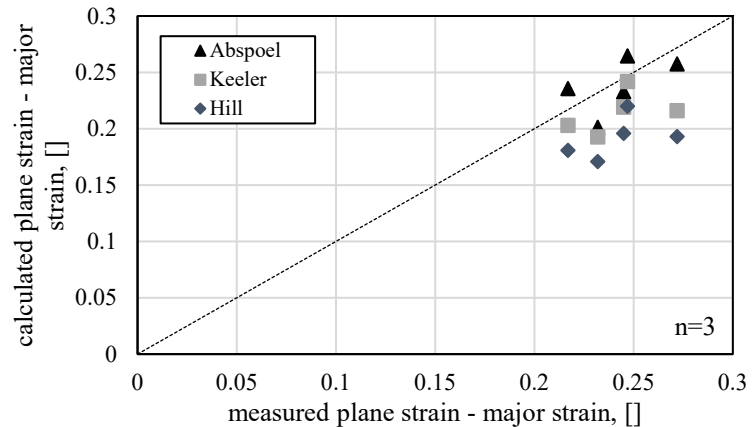
Figure 4 presents the results for the limiting drawing experiments. In figure 4 (a) the results are given as an example for the HF200 where eight different combinations of drawing ratio and blank holder force where investigated. The drawing limit is marked as a line for different blank holder forces interpolating the tear off points.
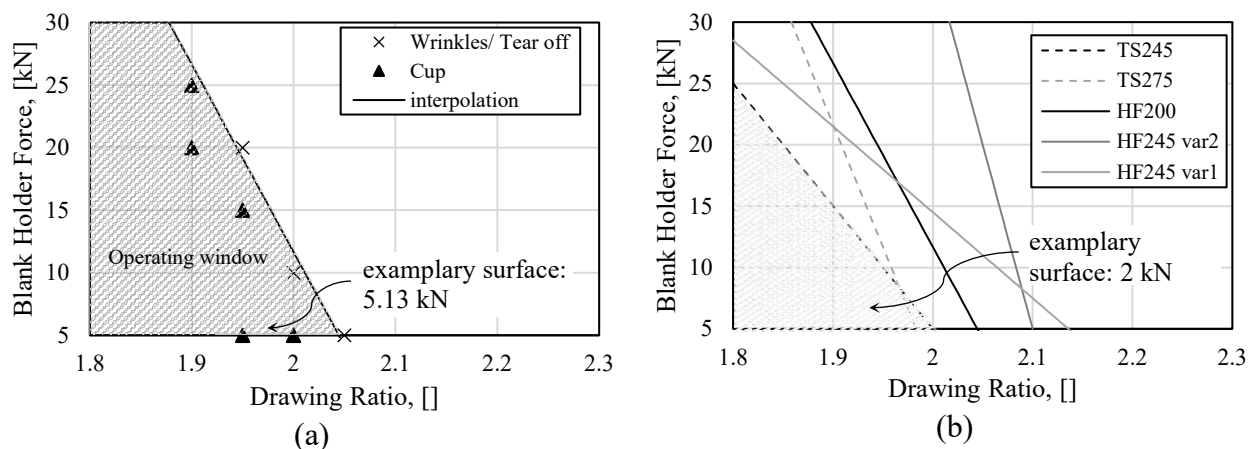

(a)

(b)

Figure 4: Limiting drawing ratio (a) HF200 (b) Comparison of different tear off limit for different packaging steels

As only an upper line exists, it becomes obvious that for the investigated materials failure occurred mainly by tear off and not by wrinkles. Lower blank holder forces were not possible at all with the hydraulic press and therefore no wrinkle line can be presented. Figure 4 (b) reveals the comparison of the investigated materials, where the drawing windows are plotted. It becomes obvious, that the operating window for the high formable steel grades are much bigger than for the standard grades. In this work the operating window is expressed as surface under the curve for the displayed and measuring range 5kn↑ and 1.8→, this means 14.18 kN (HF245 var2), 5.13 kN (HF200), 4.66 kN (HF245 var1) for the high formable steels and 3.85 kN (TS275) respectively 2.00 kN (TS245) for the standard materials. Besides the mathematical description the operating window represents the window size where a cup without wrinkles and can be formed. This confirms also the higher formability of the HF-steel grades in comparison to the standard deep drawing specifications. A bigger operating window directly means a much more stable application process as the risk of tear off is minimized. However, the conduction of this experiment is quite extensive, as at least up to ten

different drawing operations have to be conducted each with a number of five reproduction samples. Therefore, there is a big interest in getting a simple test to assess the drawing capability of different packaging steels without high experimental effort. As above mentioned, for deep drawing applications, the plane strain forming limit is important as failure occurs mainly in the punch radii where this forming condition is present. Therefore, the plane strain forming limit either determined experimentally or calculated is supposed to be able to predict the drawing capability as it is described by the limiting drawing diagram.

Figure 5 provides the comparison between drawing capability and plane strain forming limit for the experimental determination. At the one hand in figure 5 (a) the experimental plane strain forming limit is plotted as a function of the introduced drawing window surface. In figure 5 (b) the corresponding forming limit is plotted as a function of the limiting drawing ratio at a blank holder force of 15 kN. For both, a high correlation is obvious meaning 0.86 for the drawing window surface and 0.98 for the limiting drawing ratio at a fixed blank holder force. This offers high potential to predict the drawing capability of packaging steel with the experimental plane strain Nakajima test for the investigated materials. However, the effect of different strain-rates in Nakajima and cup drawings was not considered, and might have an influence on the result as well.
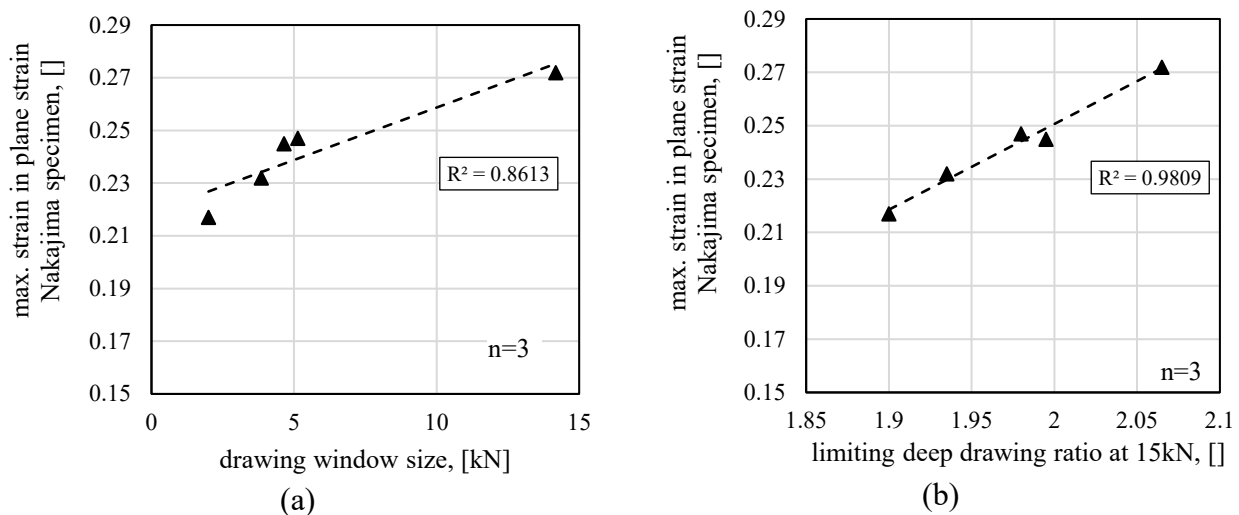

(a)   (b)

Figure 5: Comparison of drawing ratio to maximum occurring major strain in plane strain Nakajima specimens for five packaging steels

As for the most packaging steels only tensile tests are standardized conducted, there would be a great benefit in assessing the drawing capability only by this test. Therefore, also the out of tensile tests calculated plane strain forming limit was compared to the limiting deep drawing ratio at a fixed blank holder force. In figure 6 the predicted plane strain forming limit is plotted as a function of the limiting deep drawing ratio for the five investigated materials and the three introduced models. The results exhibit, that no model is able to show a strong correlation and thus the possibility to assess the drawing capability of packaging steel. The correlation coefficients range from 0.18 for the

Figure 6: Correlation between drawing capability and predicted plane strain forming limit for different calculation models.

Hill model up to 0.30 for the Abspoel model. According to the observations before, the Abspoel model provides the highest prediction accuracy but it is still much too far away from a high correlation. Thus, it can be stated, that calculation models based on tensile test data both theoretical and phenomenological fail in predicting the drawing capability of the investigated packaging steel.
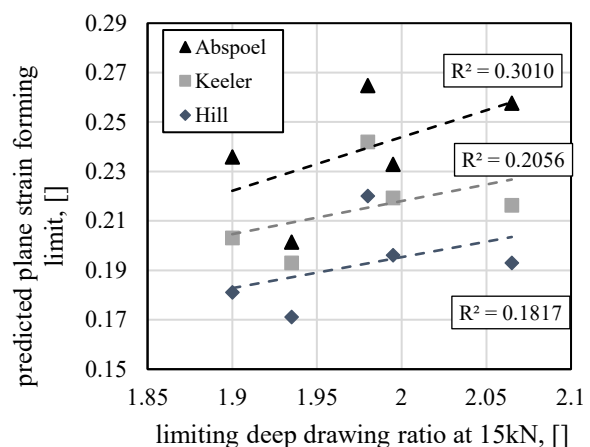
Summary

Based on the main findings in this work the following statements can be summarized:

- For the forming limit curve as well as for the limiting drawing ratio experiments, differences could be observed for the five investigated deep drawing packaging steels. The high formable steel grades showed a higher plane strain forming limit as well as a higher operating drawing window in the limiting drawing ratio experiments.

- The plane strain forming limit as it was measured in Nakajima experiments showed a very strong correlation to the size of the operating drawing window and offers thus the potential to assess the drawing capability of packaging steel by a simple test.

- Calculation methods to predict the plane strain forming limit were able to predict the occurring experimental values approximately but failed in predicting the drawing capability of the five investigated packaging steels precisely as measured by limiting drawing ratio experiments.

This investigation was limited to the results of five different packaging steels. To confirm the results a higher database of different packaging steels should be considered. As well the strain-rate dependency of packaging steel was not considered and is supposed to have an influence on the reached strain. Furthermore, for the calculation models, only quite simple models were used. In future, also more complex models, which consider Lankford coefficients by using yield locus models, should be added as for the example the model by Hu in 2018 [11].

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