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Consideration of the reduced formability of a shear cut edge in numerical forming simulation of steel sheets

Matthias Schneider[1], Thorsten Beier[2], Patrick Larour[3],
Eisso Atzema[4], Matti Teschner[1], Sebastian Westhäuser[1],
Martin Bülter[5], Michael Braun[1], Thomas Müller[5]
Arno Richter[6], Stefanie Brockmann[7]
[1] Salzgitter Mannesmann Forschung GmbH,
[2] thyssenkrupp Steel Europe, [3] voestalpine Stahl,
[4] Tata Steel, [5] SSAB, [6] ArcelorMittal, [7] Steel Institute VDEh

1 Summary

The formability of high strength steel can be significantly reduced in the case of shear cut edges. Thus, the formability of the affected edge cannot be predicted by a forming limit curve according to ISO 12004. Three different additional experimental approaches, known from literature are described to determine the formability of a specimen with a shear cut edge. Dual phase steel CR440Y780T-DP is chosen with deliberately high edge-crack sensitivity. The fracture strains of three experiments close to the cut edge are determined globally and locally, compared and analyzed. In a next step, the common forming limit diagram is extended with these limits for edge strains. In order to test the quality of crack prediction of this approach, some forming trials are performed using the so-called Smiley-tool. The formed parts are analyzed with an optical strain measurement. This data is used to ensure the correctness of the global strain distribution of the numerical simulation. Appropriate models are developed for LS-DYNA, PAM-STAMP and AUTOFORM. To achieve comparable results, the same element size is used in the three different numerical simulations and software specific features are not activated. The numerical and experimental results show a sufficient accordance in the interesting zones with shear cut edges. The extended forming limit diagram predicts all relevant cracks which occurred in the forming trials. However, although the approach of experimental determination and numerical prediction of edge-cracks show good results, still some more experimental backup is needed.

2 Keywords

Steel, shear cutting, edge-crack sensitivity, hole expansion ratio, edge forming limit, numerical simulation, forming limit diagram, hole tensile test, ISO 16630

3 Introduction

The formability of high strength steel can be significantly reduced in the case of shear cut edges [1]. Materials showing this characteristic are called edge-crack sensitive. Thus, the formability of the affected edge cannot be predicted by a forming limit curve (FLC) according to ISO 12004 [2]. If the formability of the shear cut edge is still estimated by a standard forming limit diagram (FLD), the formability would be overestimated in the simulation. To avoid such a misinterpretation an experimental determination of the formability of a shear cut edge is needed [3]. Additionally, an approach is required to use this edge forming limit in a numerical feasibility study.

4 Material and its mechanical properties

For this investigation a batch of CR440Y780T-DP [4] is deliberately chosen due to its high edge-crack sensitivity. This characteristic cannot be recognized in a standard tensile test. Here, the yield strength (R_e=574 N/mm²), the uniform elongation (A_g=10,9 %), the tensile strength (R_m=882 N/mm²) or the elongation at fracture (A_{80}=17,5 %) do not hint at the low formability of a shear cut edge. Therefore, this batch is a good representative.

5 Experiments to determine edge forming limit

5.1 Hole expansion according to ISO 16630

The hole expansion test according to ISO 16630 [5] is currently the only standardized edge-crack test method. The experiment is carried out in two steps. First, a hole with a diameter of 10 mm is punched into the sheet metal specimen with a relative cutting clearance c of 12%. It is calculated with equation 1 based on the sheet thickness s, the punch diameter d_P and the die diameter d_D.

$$\boldsymbol{c}\,[\%] = \frac{\boldsymbol{d}_\mathbf{D} - \boldsymbol{d}_\mathbf{P}}{\mathbf{2} * \boldsymbol{s}} \cdot \mathbf{100} \qquad \mathbf{1}$$

Subsequently, the hole is expanded with a conical punch (head cone angle: 60°). As soon as the operator can perceive a crack running through the entire sheet thickness, the test has to be terminated immediately. The characteristic value of this test is given by the so-called hole expansion ratio λ, which is defined as the ratio of the final hole diameter D_h compared with the initial hole diameter D_o as described in equation 2 [5]. A drawback of this test method is its high result scattering [6].

$$\boldsymbol{\lambda} = \frac{\boldsymbol{D}_\mathbf{h} - \boldsymbol{D}_\mathbf{o}}{\boldsymbol{D}_\mathbf{o}} * \mathbf{100} \qquad \mathbf{2}$$

5.2 “Hole expansion with Nakajima punch”

In addition to the standardized hole expanding test, there are numerous other test methods that have been developed in order to quantify edge-crack sensitivity [7].
The test setup for determining a forming limit curve is used for the "Hole expansion with Nakajima punch”. As in the case of the ISO 16630 hole expanding test, the test consists of two steps. First, a hole (diameter: 20 mm) is made in a square specimen (edge length: 200 mm) by punching (die clearance: 12%). In the second step, the specimen prepared in such a way is expanded with a hemispherical punch (diameter: 100 mm). On the basis of the ISO 16630 hole expanding test, the selected punch speed must be less than or equal to 1.0 mm/s. The specimen must be placed in such a way that the punching direction corresponds to the forming direction. The specimen must be precisely centered to achieve reliable results. The test is immediately stopped as soon as a crack extending through the entire thickness of the sheet metal can be detected. As in the case of the ISO 16630 hole expanding test, at least three specimens are tested per setting. The crack initiation occurs more abruptly in the "Hole expansion with Nakajima punch" than in the ISO 16630 hole expanding test [8]. For this reason, a crack width correction, as presented in [9], should be performed in the evaluation. Based on this data, the hole expansion ratio can be calculated as already described. However, in contrary to the ISO 16630 hole expanding test, a stochastic pattern can be applied to the

surface of the sheet metal before forming and a detailed strain analysis for the region of the specimen close to the edge can be performed using the ARAMIS optical measurement system from the company GOM. In the case of the hole expansion according to ISO 16630 a comparable analysis is not possible using a standard ARAMIS system, because the specimen surface is moved out of the recording area of the cameras during the test. The crack initiation and the hole expansion ratio can be automatically detected and determined by means of an evaluation macro based on Visual Basic, which contains defined crack criteria [10].

5.3 "Hole tensile test" according to Watanabe and Tachibana

For the edge-crack test "Hole tensile test", a rectangular tensile specimen is used (250 mm x 40 mm) in accordance to Watanabe and Tachibana [11], in which a hole having a diameter of 10 mm is punched in a centered manner (cutting clearance: 14 % in accordance to [11]). Then the specimen is drawn using a tensile test machine at a speed of 10 mm/min until a crack is initiated at the hole edge. In contrast to the procedure as per [11], the characteristic value is determined virtually. As in the case of the "Hole expansion with Nakajima punch", a stochastic pattern is used so that the displacements and therefore the strains in the hole region can be detected using the ARAMIS measurement system. The specimen is evaluated by means of a virtual measurement length. In the initial state, this measurement length has a length of 2 mm and a distance from the cutting edge of 1 mm and is oriented in the direction of the longitudinal axis. The characteristic value of this test method is given by the ratio of the extension of this measurement length at the start of cracking to the initial measurement length.

5.4 Comparison of test results

In Figure 1 the results of the three different edge-crack methods are shown. In order to ensure the use of the characteristic values in the following numerical forming simulation, the results are given as logarithmic strains and are called "edge limit strain". The results for hole expansion test according to ISO 16630 and "Hole expansion test with Nakajima punch" were determined with the aid of a measuring slide (left two bars in Figure 1). In this evaluation method, the strain is averaged along the circumference of the punched hole, whereby the strain reference length is comparatively large. The very local strain in the area of the later crack formation is not separated. If it is of interest how the material locally deforms, it must be evaluated with smaller strain reference lengths. In the case of the edge-crack tests "Hole expansion test with Nakajima punch" and "Hole tensile test", corresponding strain analyzes are available using the ARAMIS system from GOM as described above. The corresponding results are shown in the two right-hand bars of the diagram. It is found that the measured edge formability increases with a smaller strain reference length. In general, the used strain reference length should correspond in the experiment to the element size in the later forming simulation. This also applies when comparing different experimental test methods.

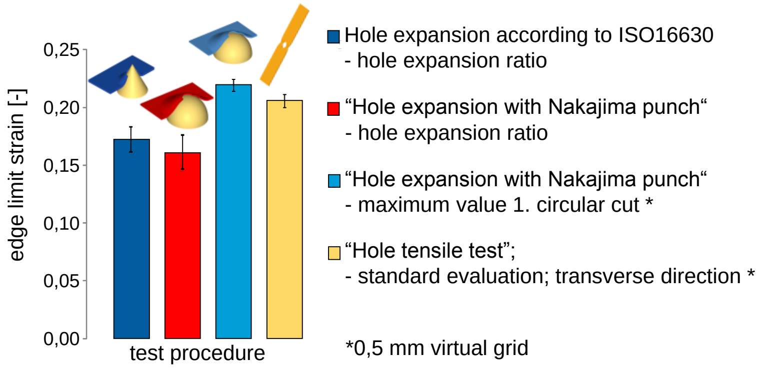

Figure 1 Comparison of the edge limit strains of three different edge-crack tests and different evaluation methods

6 Forming simulation and experiment

6.1 Experiments with the Smiley-tool

A single acting 630 t hydraulic press (max press force 630 kN, 150 bar blank holder force without spacers, 95 mm/s drawing speed, PL61 lubrication 1.5 g/m^2) has been used. The blank holder force increases linearly from 900 kN up to 1350 kN at maximal drawing depth of 87-88 mm. A cutting step (at around 10 % relative cutting clearance) and stretch flanging operation are performed after deep drawing with corresponding modular tools. The 700x540 mm sheet blank geometry (700 mm in longitudinal direction) with cut corners and an asymmetrical one sided draw bed is given in Figure 2. Edge-crack investigations have been performed both in the pre-strained & stretch flanged V-section as well as in the stretch flanged S-section. It is referred to Larour et al. [12] for more details on Smiley experimental set up.

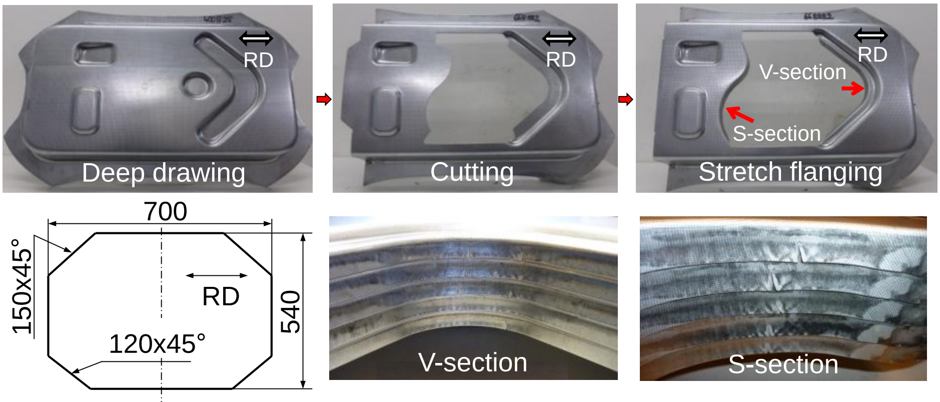

Figure 2 Deep drawing, cutting and stretch flanging operations. Sample geometry and edge-crack experimental results (Smiley V- and S-sections)

6.2 Numerical models of the Smiley forming experiments

According to the existing material parameters and tool shape the FEM models for three commercial available FE-Codes are built up. The used FE programs are AUTOFORM R6, LS-DYNA R8.0.0 and PAM-STAMP v2015.1. For a better comparison it is the aim to keep the settings almost comparable for all three programs, although a more suitable setup for each program itself would be possible. The mesh sizes for tool surfaces and the blank are similar, only the element type for the blank differs. In AUTOFORM a triangle mesh has to be used. The element size for the blank is 1mm. Adaptive refinement was not used. Tool displacements are identical. An exemplary picture of the forming process is given in Figure 3. Blankholder pressure, lubrication and blank position are optimized for each program to obtain a good agreement to the measured draw-in. This is essential for the comparison of the experimental measured and the calculated strain distribution after OP20.

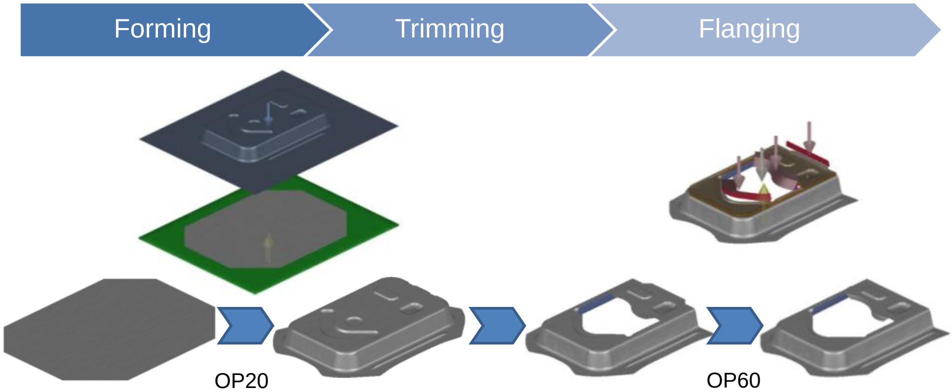

Figure 3 Schematically description of the forming process

For the description of the material behavior in each program several hardening and material laws are available. In some cases the implementations may differ a little bit. To obtain a basis for comparison the material law Hill `48 is chosen. It also represents a standard basis model for the use in industrial forming simulation. In the past good results have been made for DP-steels by using this material law [13]. The Hill `48 model is easy to fit by using the r-values in 0°, 45° and 90° to rolling direction derived from tensile tests. An optimal material description may be possible by using more complex advanced material laws, which also require additional non standardized tests for calibration. But the expected improvement in this case would only be marginal.

To describe the hardening behavior of the investigated material the yield curve obtained from tensile tests is extrapolated for high strains by the use of the hydraulic bulge test according to ISO 16808 [14]. Additional for the prediction of failure due to necking the Forming-Limit-Curve is needed. In this case a calculated FLC is used [15]. The components of the material model are illustrated in Figure 4.

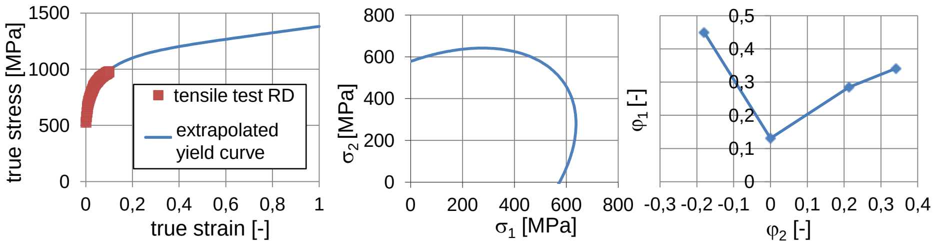

Figure 4 Material data used in finite element model; left: hardening curve, middle: yield locus, right: FLC

6.3 Program specific commands

6.3.1 <u>LS-DYNA</u>

For the evaluation of edge-cracks in FEM forming simulation, an adequate mesh at the cutting edge is to be ensured. When elements generated by the trimming process at the edge, the element distribution can be controlled by TCTOL=1.0 in the definition of the trimming curve (knows: no new elements created, nodes just get a new position). Furthermore the minimum size of elements can be defined by the control cards ADAPTIVE CURVE and CHECK SHELL. Otherwise very small elements on the trimming-edge are generated, which lead to problems during the subsequent forming processes.
In addition to the approach shown in this work, the LS-PrePost tool (4.2) can be used to investigate the component for edge-crack sensitivity. First call the FLD-tool and select the Formability function. The derived maximum edge strain from chapter 5 is entered in the opening window. Furthermore there are 3 cutting edge qualities available (Laser cut, new punch and worn punch). So the first element row at the edge is automatically selected and colored to the edge-crack detection kit.

6.3.2 <u>AUTOFORM</u>

Cut edge failure investigations are possible with AUTOFORM since version R6. The result variable “Edge Cracks” considers the quality of a cut edge and the strain at the edge to indicate a crack. There are three different cutting qualities available called “Laser Cut”, “Sharp Steel” and “Worn Steel”. In the material definition each quality has to be defined by a critical strain which indicates an edge-crack. In the analysis for this work the derived edge forming limits in chapter 5 are used. The material parameter is called “Max Edge Strain” and has to be defined as an additional material parameter to enable the calculation of this result variable. In addition the result variable has to be activated on the Control > Results page of the Simulation stage. Similarly to surface cracks a fracture curve is derived from the critical strain defined in the material description (Max Edge Strain). The solver compares the current strain state along an edge in each increment with the critical strain given from the fracture curve and accumulates the incremental results of “Edge Cracks”. But instead of analyzing the strains in the outer layer the result of “Edge Cracks” refers to the middle layer. Similar to the result variable “Formability” the risk of “Edge Cracks” is indicated by traffic lights as well. The safety margin can be defined in the Result Variable Settings at Edge Cracks [16].

6.3.3 PAM-STAMP

PAM-STAMP offers an option to generate a better mesh quality at cut edges. In the menu “Mesh transformation” of the GUI the option “Optimize for flanging” and “Force orthogonal edges” have to be activated. This commands force the mesh algorithm to avoid triangular shell elements at the direct cut edge. The first row of four-sided shell elements additionally shows element borders which are perpendicular to the cut edge. The strain distribution of such a mesh seems more realistic as published by Gläsner et al. [17]. The postprocessing for the use of an extended forming limit diagram has to be done manually. First, the edge elements have to be selected and copied in a new part. This allows the user to visualize the “FLD (strain) Rupture Risk” in the “Contour Plot” menu explicitly for the edge elements. The fiber with highest major strains at selected elements has to be selected to achieve a right estimation.

6.4 Comparison of experimental and numerical results

To compare the experimental and virtual forming results, the so called Smiley-tool was examined by the optical measuring system ARGUS of the company GOM. In addition to the geometry, the measuring system also provides measuring variables such as the distribution of the major and minor in-plane strain, which can be used for comparison. The results of the forming simulation can be projected on the surface of the ARGUS model using the SVIEW module within ARGUS. The formation of differences between the experimental and virtual distribution enables a clear plot or comparison of the forming results between the three used software-tools. Figure 5 shows for example major in-plane strain distribution of the V-section. In this area edge-cracks occurred during the experimental investigations.

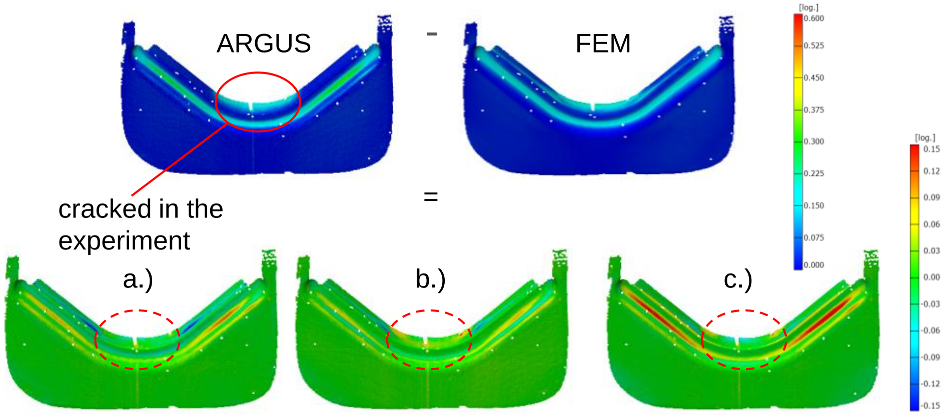

Figure 5 Major in-plane strain from experimental component measured by ARGUS-System and the difference between measured and calculated major in-plane strain for LS-DYNA (a), PAM-STAMP (b) and AUTOFORM (c)

In the lower part of Figure 5, blue indicates higher strains and red lower strains. Especially too small strains could lead to an overly optimistic feasibility analysis. Furthermore, the radii in all three programs cannot be optimally reproduced by the specification of the element edge length. By adapting the models, improvements of accuracy are certainly feasible, but for a better comparability this was neglected. For a more detailed analysis of the V-section, the agreement at the edge is sufficient.

7 Estimation of edge-cracks using an extended forming limit diagram

Based on the approach from McEwan et al. [18] a standard FLD is extended by the experimentally determined edge forming limit. In Figure 6 the FLC is shown for the investigated material. In the region of uniaxial tension a horizontal line for the major true strain determined by the hole expansion according to ISO 16630 [5] and the “Hole tensile test” according to Watanabe and Tachibana are added [11]. Due to the deviation of the relative cutting clearance in characterization and forming experiment, a tolerance zone of ± 0.015 is added to this tight limit.
The results from the three programs are added to the diagram. Thus, an exceeding of the edge forming limit is predicted. Here, in forming experiment a crack has occurred.

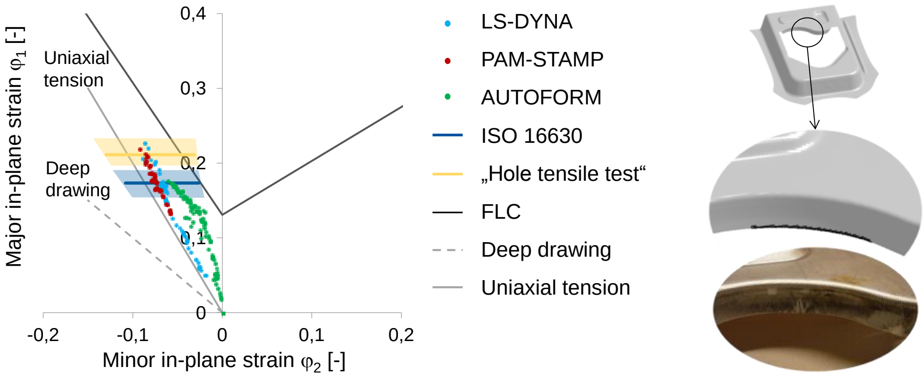

Figure 6 Extended forming limit diagram for the S-section of the Smiley-geometry for LS-DYNA, PAM-STAMP and AUTOFORM

The V-section of the Smiley-geometry has a pre-strain due to an embossing in a prior forming step. Adding the results from the three programs to the extended FLD, a deviation from the strain path of uniaxial tension is visible, as documented in Figure 7.

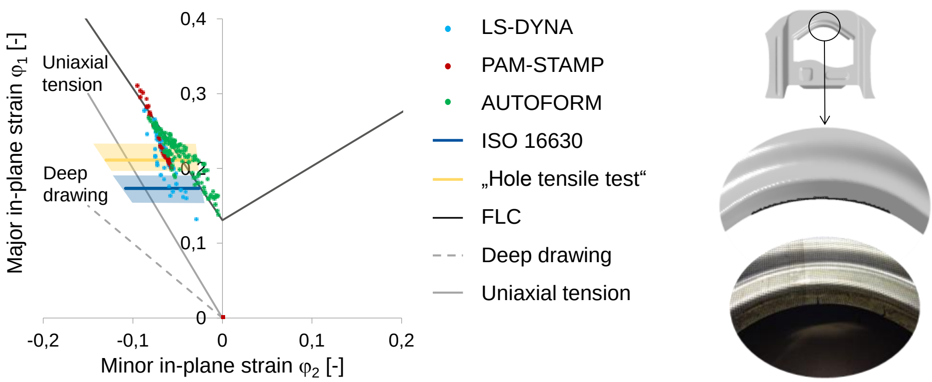

Figure 7 Extended forming limit diagram for the V-section of the Smiley-geometry for LS-DYNA, PAM-STAMP and AUTOFORM

If the amount of pre-strain is neglected and only the strain data after the cutting operation is used the conditions of uniaxial tension are better fulfilled. The overshooting of the edge forming limit fits to the cracks in the forming experiment.
It has to be pointed that each software tool has specific features to visualize and predict possible edge-cracks which have not been shown in this work in detail.

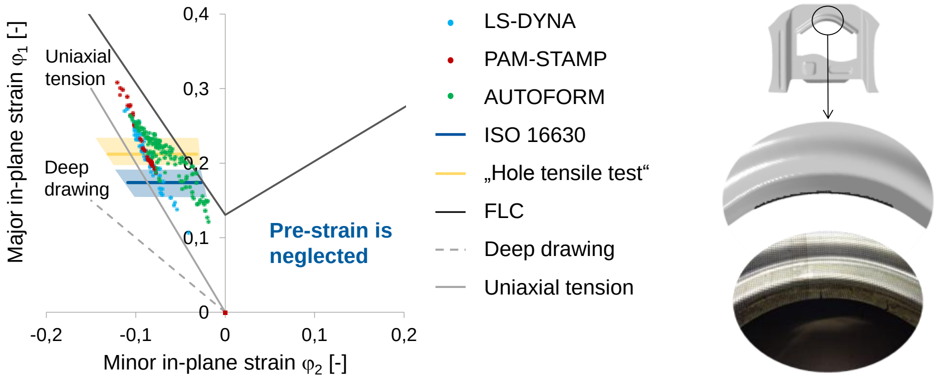

Figure 8 Extended forming limit diagram for the V-section of the Smiley-geometry for LS-DYNA, PAM-STAMP and AUTOFORM with negligence of pre-strain

8 Conclusion and outlook

The experimental investigation on the formability of a shear cut edge of a steel sheet show that the reduction of formability due to shear cutting can be significant. There are several experimental procedures known in literature. In this paper the hole expansion according to ISO 16630 [5], the “Hole expansion with Nakajima punch” [19] and the “Hole tensile test” according to Watanabe and Tachibana are performed [11].
As a global measurement the hole expansion ratio is more conservative than the results from local strain measurement. For an adequate comparison of experimental results, a similar virtual strain gauge is mandatory.
The experimentally determined edge forming limit can be used to extend the well known forming limit diagram as suggested by McEwan et al. [18]. This pragmatic approach is realizable with industrial finite-element-software as LS-DYNA, AUTOFORM and PAM-STAMP. With these three programs the experimental observed edge-cracks can be predicted.
However, the approach needs more experimental backup. Additionally, the effect of a significant amount of pre-strain on the edge forming limit has to be further investigated.

9 Acknowledgements

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