FORMING BEHAVIOR ABOVE THE CLASSICAL FLC-LIMITS - EXPERIMENTAL METHODS AND NUMERICAL MODELS FOR THE PREDICTION OF SHEET CRACK PHENOMENA

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ABSTRACT: The industrial based prediction in sheet metal forming bases still on the Forming Limit Diagrams (FLD) as formally proposed by Keeler [1]. The FLD are commonly specified by the Nakajima tests and evaluated with the so called cross section method. Although widely used, the FLC concept has numerous serious limitations. In the paper the possibilities for a specific prediction of crack limits based on an extended FLC concept (X-FLC) will be discussed. The new concept demonstrates that the Nakajima tests are not only appropriate for the evaluation of the necking instability but for the detection of the real crack strains too. For the evaluation of the crack strains a new local thinning method is proposed and tested for special 6xxx Al-alloys.

KEYWORDS: Localized necking, fracture strain, FLC, extended FLC

1 INTRODUCTION

In the sheet metal forming beside the limits induced by flow instability which results in localized necking also crack phenomena occurs. Those are cracks induced by hemming, cracks induced by small die curvature radii, edge cracks as well as shear cracks. The corresponding strains are usually strongly higher than the instability limits predicted by FLC’s and needs another theoretical approach.

In the sheet metal forming there have been different approaches e.g. [3], [4] and others to specify the corresponding stain limits by additional curves in the FLC diagrams.

Another approach was initiated by Wierzbicki and his co-authors Bai and Bao [2] who introduced extended Johnson-Cook models with the additional influence of the Lode-Parameter $L$. In this way the strain limits will be defined in dependency of stress parameters $\eta = \sigma_{yy} / \sigma_{eq}$ and $\xi = L$ instead in dependency of strains as used in the FLC-concept.

As difficulties in the application of the triaxiality method two aspects have to be mentioned: the evaluation of different stress stats requires very complex specimens (s. Fig. 3), which cannot be fabricated of thin sheet materials and due to the fact, that the stress-ratios changes during the experiment the parameters are path dependent and will be used in the diagram only as average values. This aspect was more deeply discussed by Gorji [6].
It was shown by later investigations of the authors and by Mohr [12], that the first published experimental results were even very un-accurate and in a sense misleading.

The contribution will discuss a new experimental testing method based on a special Nakajima specimen evaluation method. The so evaluated crack limits will be compared with different theoretical failure criterions. It will be demonstrated that the Nakajima-based evaluation method has the potential to substitute the industrially applied bending test and the hole expansion test and allows a generalized crack limit approach.

In the second part of the talk a LS-Dyna FEM implementation for the prediction of the crack limits will be presented. The proposed methods will be validated on a recently developed deep drawing test part.

2 PHYSICAL DEVELOPING OF NECKING AND RUPTURES

Before the introduction of the new experimental method, we would like to point out following behaviour.

The failure process of ductile materials is pre-induced by a collapse of the plastic deformation zone. In Fig. 4 the red zones show the still active plastic zones.

Considering the major strain along a cross section, Fig. 5, it will be very clear, that the necking is a continuously increasing process running up to rupture.

In contrast to this physical behavior the FLC evaluation methods specified by ISO/DIS 12004-2 evaluates a critical deformation state which approximatively corresponds to the yellow curve in Fig. 5. Thus, the defined Forming Limit Curve does not describe the physical crack, but is more or less a technological limit defining the possible forming before significant necking arrives. The often used remark “crack zone” for strains above the FLC-line, Fig. 6, is physically incorrect. In this zone a conditionally stable or conditionally unstable behavior arrives. Processes like hemming or incremental forming, which are stabilized by stable material around the forming zone (corresponding to specific boundary conditions) behave even in this strain region without any problems. This is the reason, why the “classical” Nakajima FLC than move to higher values – partially named as “Bending Limit Curve” or real “Crack Limit Curve”. For the prediction of the crack behavior it is of significant importance to interpret this behavior in a physically correct way.
The methods for the determination of the “extended” FLC diagrams will be explained in chapter 4 of this paper. Specifically for the Al-material AA6016 the so derived X-FLC plot is given in Fig. 11 for a monolayer material.

3 LIMITATIONS OF STANDARD FLC PREDICTION METHODS

The standard FLC evaluation methods bases on Nakajima tests which use spherical punches with diameter of 100.0 mm. For sheet thicknesses of 1.0 mm the bending influence is then negligible. For those reasons the FLC describes only the necking behaviour for practically flat sheets. If the t/r ratio becomes significant, the FLC will be transformed to higher values. A more detailed discussion about the influence of the curvature on the FLC can be found in Hora et al. [10] (Numiform’16).

3.1 INFLUENCE OF BENDING EFFECTS ON DEEP DRAWING BEHAVIOUR

How significant the bending influence is, can be demonstrated by following example. Fig. 9 shows a deep drawing example with a die radius of r=3.0 mm for the material AA6016.

![Fig. 7 Extended FLC methods including the crack phenomena descriptions](image)

![Fig. 8 FLC based prediction of the critical depth. Die radius 3.0 mm, material AA6016. Experiment ca. 29 mm. theoretical prediction 16 mm Gorji [5],[6]](image)

The cracks in the region of the die curvature will be often identified as “shear cracks”. An investigation done by Gorji et al. with different square blanks and different blank holder forces demonstrated, that dependent on the selected parameter combination the localized necking occurs as classical bottom neck or as a upper radius crack.

By increasing the die radius to r=5.0mm the upper neck disappears.

![Fig. 9 Formability diagram of AA6016 sheet sample, Gorji [8]](image)

Fig. 8 demonstrates that a FEM simulation based on shell elements and classical FLC is not able to predict this influence correctly.

4 EXPERIMENTAL DETECTION OF CRACK LIMITS

For the evaluation of such shear cracks the physical strain crack limits $\varepsilon_{\text{maj}}^{\text{maj}}(\beta)$ and not the classical $\varepsilon_{\text{maj}}^{\text{FLC}}(\beta)$ are needed.

In contrast to the “Wierzbicki” specimens the goal was to use the established “standard” sheet tests. For this reason, the authors proposed the combination of two methods – the Nakajima tests combined with an additional cup drawing test for detecting the behavior for $\beta < -0.5$

4.1 EXPERIMENTAL DETECTION OF CRACK LIMITS BASED ON NAKAJIMA TESTS

The first method evaluates the crack strain based on the thinning strains (“Thinning Method”) measured on the fractured Nakajima specimens. The detailed evaluation procedure is given in [6] and [8].
In many deep drawing applications, the largest strains occur on the left side of the FLC. For those reasons a special DD test with a quadratic blank and a relatively small die curvature of $r=3.0 \text{ mm}$ was applied to get an additional “point” specifically in the deep drawing (compression-tension combination) range. The experiment with the corresponding strain distribution at the crack time step shows Fig. 12.

The combination of the Nakajima fracture strains with the additional DD fracture strains can be used as data base for the determination of a generalized fracture line.

5 LAYER BASED FAILURE PREDICTION WITH SHELL ELEMENTS

The classical failure predictions bases on a mono-layer FLC prediction.

If the fracture is initiated by a surface crack, as it is the case by small radii, an extended X-FLC method has to be applied. The crack develops and initiates only when the outer layer reached the crack limit.

4.2 EXPERIMENTAL DETECTION OF CRACK LIMITS BASED ON DEEP DRAWING TESTS

The Nakajima based test are restricted to the stress range

$$0 \leq \alpha = \frac{\sigma_x}{\sigma_1} \leq 1.0$$
The FEM-implementation was done in that way, that the crack failure was checked specifically for each layer. If the critical stain was detected above the fracture line, the specific shell layer was deactivated, see Fig. 14. In the LS-Dyna code the implementation was done by the subroutine UMAT41.

The *PART COMPOSITE functionality of FE-code Ls-Dyna has been employed instead of the regular shell element. The latter case requires material properties of the homogenized Fusion as a single material whereas in the composite shell element, the mechanical properties and thickness distribution of each layer can be separately described. Eleven integration points (IPs) through the thickness of the composite shell elements are employed to characterize the multilayer Fusion material. One IP for each clad outer layer with the thickness of 0.06 mm and nine IPs for the core with thickness of 0.0978 mm for each layer with total core thickness of 0.88 mm. Defined integration points of the core and clad have their own material properties i.e., hardening curve, standard or modified Yld2000-2d yield function and fracture limit.

Fig. 14  Implementation in the user subroutine UMAT41: 1st computation of the principal strains from the strain tensor, 2nd comparison of the computed principal strains with the fracture line, 3rd if the computed strains are above the fracture line, then set all stress components to zero.

5.1 PREDICTION OF CRACK LIMITS FOR PARTS WITH SMALL DIE RADII AND A MONOLAYER STRUCTURE

For the validation of the above implementation a so called “triangle” test part was used. Fig. 15 shows the crack position on the real part. The critical depth was at \( H \approx 43 \) mm.

In the case of a simple “monolayer” FLC evaluation the predicted forming depth lies at \( H = 29 \) mm. It is obvious that not only the predicted part depth of 29 mm instead of 43 mm but also the position of the crack are not correctly predicted.

Fig. 15  Triangle part. Monolayer material AA6016. Critical depth \( H = 43 \) mm

With the alternative method, applying the extended X-FLC of Fig. 13, the failure can be identified correctly, Fig. 17.

Fig. 16  Triangle part. Monolayer material AA6016. Prediction of critical depth based on a monolayer FLC: \( H = 29 \) mm

Fig. 17  Material AA6016. FE Simulation of triangular experiment with Linear fracture criterion (strain distribution of lower, middle and upper-layer)
5.2 PREDICTION OF CRACK LIMITS FOR MULTILAYER FUSION MATERIALS

A more complex behavior is given when multilayer materials like the multilayer composite FUSION\textsuperscript{TM} [Novelis] is applied, Fig. 18.

The material is composed of a soft AA5005 alloy outside (clad) and a hard AA6016 alloy inside (core) Fig. 18 bottom demonstrates again clearly how significantly the DD behavior changes. As reasons for the increase of the strain limits, the change of the strain distribution in the sheet plane as well as strain gradients over the thickness can be seen as the influencing effects.

The thickness strain gradients depend on the ratio $\chi = t/r$. In the current DD examples with the die radius of 3.0 mm the critical ratio was about 0.3.

If the monolayer material is replaced by the FUSION multilayer material as introduced in Fig. 19, the failure can be completely avoided.

For the simulation of the FUSION behaviour the X-FLC diagrams have to be specified separately for the core and clad material. Interesting in this case is that the FLC’s are the same for the soft (clad) and the hard (core) materials but the fracture lines reach strongly different levels, Fig. 20.

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5.3 PREDICTION OF CRACK LIMITS IN A HOLE EXPANSION TEST

From the industrial point of view edge cracks often occur on sheet parts. Some detailed investigation has been recently published by Larour et al. [11]. In this investigation among others the quality of the edge can be identified as a significant parameter.

In the example presented below, an aluminium material AA6016 in the sheet thickness of \( t = 1 \) mm was applied. The material data are specified in Hora et al. [9]

<table>
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<tr>
<th>FlC evaluated for the material AA6016</th>
<th>( \varepsilon_2 )</th>
<th>( \varepsilon_1 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>-0.215</td>
<td>0.43</td>
<td></td>
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<tr>
<td>-0.086</td>
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<td>0.28</td>
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</table>

Fracture strain: \( \varepsilon^f = 0.45 - 0.42 \varepsilon_2 \)

Using the X-FLC model with the fracture line evaluated with the thinning concept, Fig. 10, the simulation delivers obviously a very correct prediction for the critical state, Fig. 24.

The experimental results of the Marciniak hole expansion test are plotted in Fig. 23. To avoid “undefined” edge damage the inner hole was wire cutted.
6 CONCLUSIONS

The contribution demonstrates on selected examples that the classical FLC prediction is not applicable if the parts have either small die radii or are composed by layers with different properties. In this case beside the FLC a crack limit curve has to be specified too. For the detection of such critical strain the presented thinning method, evaluating the fracture strains on Nakajima specimens, have been used. The multi-layer failure identification was implemented in to the explicit FEM code LS-Dyna.

REFERENCES