Modelling of fracture effects in the sheet metal forming based on an extended FLC evaluation method in combination with fracture criterions

P Hora¹, M Gorji¹, and B Berisha¹

¹ ETH Zurich, Institute of Virtual Manufacturing, Tannenstr. 3, 8092 Zurich, Switzerland

E-mail: hora@ivp.mavt.ethz.ch

Abstract. The industrial based prediction in sheet metal forming bases still on the Forming Limit Diagrams (FLD) as formally proposed by Goodwin [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 local thinning method as proposed by Gorji et al. [3] is applied and tested for special 6xxx and 5xxx Al-alloys as well as for the corresponding multilayer FUSION material.

1. Introduction
In the sheet metal forming beside the limits induced by flow instability which results in localized necking also crack phenomena occurs.

Various crack types can occur e.g. cracks induced by hemming, by small die curvature radii, edge cracks as well as shear cracks (s. Figure 1). The corresponding strains are usually considerably higher than the instability limits predicted by FLC’s and need another theoretical approach.

In the sheet metal forming there have been different approaches e.g. [7] and [8] to specify the corresponding strain limits by additional curves in the FLC diagrams.
Figure 1. Different type of cracks in sheet metal forming: (left) Die bending crack, (middle) Hole expansion edge crack; (right) Hemming surface crack, Gorji [4].

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

Figure 2. Characteristic shape of a triaxiality diagram [2].

Concerning the 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. Figure 3), which cannot be fabricated of thin sheet materials and due to the fact, that the stress-ratio 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 [4].

Figure 3. Proposed specimens for the evaluation of the triaxiality diagrams, [2].

Because of the mentioned weaknesses of the triaxility experiments the industrial oriented fracture tests are based typically on a bending test and on a hole expansion test, see Figure 4.
The presented contribution shows a generalized crack prediction concept based only on Nakajima tests in combination with a special deep drawing test. The so detected experimental data will be approximated based on 4 different crack criterions, highlighting the newly introduced linear fracture line by Gorji et al. [5].

In addition to mono-layer materials also a multi-layer material, FUSION™ [Novelis], has been investigated, see Figure 5. It is composed of a soft AA5005 alloy outside (clad) and a hard AA6016 alloy inside (core). The layer specific failure prediction is indispensable for multi-layer materials with strongly different behavior of the layers, as will be shown in chapter 5.

Figure 5 right shows that both materials, core and FUSION, have practically the same yield curve, whereas the yield curve of the clad material is much lower. The crack-prediction method – linear fracture line - will be demonstrated in an application on a part called “triangle test” with a very small curvature radius of 3 mm for two different materials: in Figure 18 for a mono-layer AA6016 material and in Figure 21 for the multi-layer Al sheet FUSION.

2. Material data
In the framework of this investigation both materials, AA6016 and in combination with the FUSION AA5005 as clad, have been used. The specific material models are given below.

Uniaxial tensile tests and the hydraulic bulge tests were performed to determine the yield curves. The well-known Hockett-Sherby approximation has been used for the description of the core material AA6016 and FUSION AF200

\[
\sigma_y = B - (B - A) \exp\left[-m e_{eq}^n\right] 
\]

whereas for the clad material AA5005 a combined approach of Ghosh and Hockett-Sherby showed better approximation.
\[ \sigma_y = k(C_1 + C_2(C_3 + \varepsilon_{eq})^C_4) + (1 - k)(B - (B - A)\exp [-m\varepsilon_{eq}]) \]  

(2)

The parameters of the models are given in Table 1.

| Material  | A    | B    | m   | n   | C_1  | C_2  | C_3  | C_4  | k   |
|-----------|------|------|-----|-----|------|------|------|------|-----|
| AA6016    | 123.7| 352.4| 5.62| 0.87|      |      |      |      |     |
| AA5005    | 39.7 | 123  | 88.72| 1.23| 8.9  | 234.8| 0.003| 0.34 | 0.6 |
| FUSION    | 119.2| 345.4| 5.44| 0.862|     |      |      |      |     |

Further, parameters of the YLD-2000 yield loci are given in Table 2:

| Material  | \(\sigma_0\) | \(\sigma_{45}\) | \(\sigma_{90}\) | \(\sigma_b\) | \(R_0\) | \(R_{45}\) | \(R_{90}\) | \(R_b\) |
|-----------|---------------|------------------|------------------|-------------|---------|---------|---------|---------|
| AA6016    | 189.2         | 182.6            | 184              | 186.7       | 0.67    | 0.5     | 0.67    | 1       |
| AA5005    | 95.8          | 90.8             | 94.1             | 91.3        | 0.68    | 0.33    | 1.33    | 1       |
| FUSION    | 184.8         | 176.1            | 176.7            | 176.5       | 0.69    | 0.43    | 0.73    | 1       |
| AA6016    | 0.947         | 1.017            | 0.961            | 1.032       | 1.021   | 1.013   | 0.967   | 1.153   |
| AA5005    | 0.8757        | 1.1421           | 1.1462           | 1.0152      | 1.033   | 1.0469  | 0.938   | 1.1879  |
| FUSION    | 0.9201        | 1.0806           | 1.0183           | 1.0508      | 1.0377  | 1.0842  | 0.9686  | 1.1564  |

The X-FLC applies a FLC as well as the crack failure data, as shown in Figure 6 and Figure 7:

\[ \varepsilon_f = 0.45 - 0.42 \varepsilon_2 \]  

(3)

The fracture strains for the core material (AA6016) are approximated with the following linear model:
The fracture strains for the clad material (AA5005) are approximated with the following linear model:

\[ \varepsilon_f = 1.95 - 0.33 \varepsilon_2 \]

The fracture strains of the clad material AA5005 are much higher than those of the core AA6016, as shown in Figure 7 and Figure 6, respectively.

### 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 (sheet thickness to radius 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. [6].

#### 3.1. Influence of bending effects on deep drawing behaviour

How significant the bending influence is, can be demonstrated by following example. Figure 8 shows a deep drawing example with a die radius of r=3.0 mm for the material AA6016.

**Figure 7.** X-FLC data for AA5005: (left) Data based on MMFC approach (FLC-3 as shown in section 5.3); (right) The corresponding plot of the FLC and the fracture line.

The fracture strains for the clad material (AA5005) are approximated with the following linear model

\[ \varepsilon_f = 1.95 - 0.33 \varepsilon_2 \]

The fracture strains of the clad material AA5005 are much higher than those of the core AA6016, as shown in Figure 7 and Figure 6, respectively.

#### 3.1. Influence of bending effects on deep drawing behaviour

How significant the bending influence is, can be demonstrated by following example. Figure 8 shows a deep drawing example with a die radius of r=3.0 mm for the material AA6016.

**Figure 8.** FLC based prediction of the critical depth H. Die radius 3.0 mm, material AA6016. (left) Experiment H ≈ 29 mm. (right) theoretical prediction H ≈14.5 mm Gorji [3],[4].
The cracks in the region of the die curvature will be often identified as “shear cracks”. An investigation done by Gorji [4] 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, see Figure 9. By increasing the die radius to r=5.0 mm the upper crack disappears. In Figure 9 the parameter $\beta$ represents the ratio between edge length $L$ of the squared blank and the punch diameter.

![Figure 9. Formability diagram of AA6016 sheet sample, Gorji [4].](image)

Figure 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 sheets
For the evaluation of such shear cracks the physical strain crack limits $\varepsilon_{\text{maj}}^{\text{crack}} (\beta)$ and not the classical $\varepsilon_{\text{maj}}^{\text{FLC}} (\beta)$ are needed, where beta is the strain ratio $\beta = \varepsilon_{\text{maj}}^{\text{FLC}} / \varepsilon_{\text{min}}$.

In contrast to the specimens shown in Figure 3 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 behaviour 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, see Figure 10. The detailed evaluation procedure is given in [4] and [5].

![Figure 10. Evaluation of the fracture strain by the local detection of fracture thinning on the Nakajima specimens. Gorji [3],[4].](image)
Figure 11 shows the so detected crack strains $\varepsilon_{maj}^{crack}(\beta)$ for the material AA6016 in relation to the classical FLC limits evaluated by the cross section as well as the time dependent method. The parameter $B$ represents the width of the plastic zone in the so called LL-FLD (Localized Level - FLD) as proposed by Hora et al. [9]

![Figure 11. Evaluation of the fracture strain by the local detection of fracture thinning on the Nakajima specimens and comparison with the FLC. Gorji [3],[4].](image)

4.2. Experimental detection of crack limits based on Deep Drawing tests

The Nakajima based test are restricted to the stress range

$$0 \leq \sigma \leq \sigma_0$$

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 $r=3.0$ mm was applied to get an additional “point” specifically in the deep drawing (compression-tension combination) range. The evaluation of the strains is based on the comparison of the real part (height and draw in at fracture) with the FEM simulation, Figure 12. As critical fracture strain, the strain on the surface of the sheet (top layer of the shell), was defined.

![Figure 12. Calibration of the fracture line based on a deep drawing experiment and the corresponding strain distribution at the crack time step, Gorji [4].](image)

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.
4.3. Extrapolation and interpolation of the fracture points based on different failure criteria

The experimentally predefined strain has been compared with the theoretical limits of different failure criteria. The check was especially done applying following 4 different criterions:

- Maximum shear stress criterion
- Equivalent strain criterion
- Johnson-Cook criterion and
- Linear fracture line criterion

Figure 13 shows the results of the theoretical fitted failure curves with the experimental points, which were determined from the Nakajima experiments shown in Figure 10. Given that the fracture strains in the principal strain space show practically a linear distribution (Figure 13 left), it is reasonable to use a linear model for the description of the fracture behaviour. Moreover, a stable behaviour of the model is ensured, as there is no rapid change in the description of the fracture behaviour, see (Figure 13 left).

Remarkable is the fact, that all criterions fit the position of the measures points quite well, but that the criterions deviate significantly in the left “deep drawing” range. Especially this range influences strongly the virtual results for deep drawing operations.

![Figure 13](image)

**Figure 13.** Comparison of different fracture criteria in principal strain space and in triaxiality-equivalent strain space, [4].

As will be demonstrated in chapter 5 the “linear fracture line” describes the behaviour in the most accurate way and delivers for real applications the best fits with the real behaviour. The JC-criterion will deliver only slightly different results.

5. FE-Implementation of the X-FLC concept for monolayer and multilayer materials

5.1. 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 bending radii, an extended X-FLC method has to be applied, see Figure 14. The crack develops and initiates only when the critical layer reached the crack limit. Points above the FLC will then be interpreted as conditional stable (this corresponds to the real physical behaviour!) and not as usually assumed as failed by cracks.
Figure 14. Extended X-FLC description considering the fracture ("crack") limits by the bending strains.

The FEM-implementation was done in that way, that the crack failure was checked specifically for each layer. If a critical strain was detected, the specific shell layer was deactivated by setting the stresses to zero. 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. Based on this element formulation the mechanical properties and thickness distribution of each layer can be described separately. The implementation contains following main steps:

- computation of the principal strains from the strain tensor
- comparison of the computed principal strains with the fracture line
- if the computed strains are above the fracture line, then all stress components are set to zero

5.2. Validation tests

For the validation of the above implementation a new “triangle” test was designed. The tests have been done with the monolayer material AA6016 as well as with the FUSION material. Figure 15 demonstrates the significant change of the deep drawing behaviour for the both materials.

Figure 15. Triangle part - (top) Monolayer material AA6016. Critical depth H = 43 mm; (bottom) FUSION material still no failure at H=55 mm.
The crack of the AA6016 material, in the die region, is induced by the small die radius of 3.0 mm. Due to the better bending behaviour of the FUSION material, the multilayer material does not fail. This special crack behaviour can be only understood on the base of an additional fracture consideration as introduced by the X-FLC concept.

5.3. Prediction of crack limits for parts with small die radii and a monolayer structure

The experimental behaviour of the monolayer material was demonstrated in Figure 15. The rupture occurs at a depth of $H \approx 43$ mm.

Before the application of the extended X-FLC method the classical FLC approach shall be discussed. For the determination of the FLC three different methods have been compared:

- **FLC (1)** Evaluation of the Nakajima test – Cross Section evaluation method. Most left point $B_{20}$
- **FLC (2)** Evaluation of the Nakajima test – Cross Section evaluation method. Most left point $B_{50}$
- **FLC (3)** Numerically evaluated FLC – MMFC criterion [6], adjusted with FLC0 (plane strain point)

For the numerical failure prediction a relative failure value of $\varepsilon_{\text{maj}}/\varepsilon_{\text{FLC}}=1.0$ will be used as critical measure. The specific results are plotted in Figure 16: method FLC (1) delivers a critical depth of $H=22$ mm, with method FLC (2) the depth increases to $41$ mm. Method FLC(3) shows approximately the same behaviour as (2) with $H=45$ mm.

![FLC (1)](image1)

$H_{\text{FLC1}} = 22$ mm

$H_{\text{Exp}} = 43$ mm

![FLC (2)](image2)

$H_{\text{FLC2}} = 41$ mm

![FLC (3)](image3)

$H_{\text{FLC3}} = 45$ mm

**Figure 16.** Triangle part. Monolayer material AA6016. **FLC 1**: Prediction of critical depth based on a monolayer measured FLC (1): height $H = 22$ mm; **FLC 2**: the same FLC without the “tensile” point FLC (2), height $H = 41$ mm. **FLC 3**: MMFC-criterion adjusted with FLC0, height $H = 45$ mm.

The differences of the 3 methods are obviously caused by the changes of the FLC in the extrapolated left range, see Figure 17. Only a slight difference in the slope, based on the left two FLC points,
influences strongly the “classical” FLC-prediction of the critical state. In this sense the use of the Nakajima B20 specimen (method 1) is misleading, if extrapolation on the left side of the FLC is needed. The reason may be the stress boundary condition in the case of the B20 specimen instead of the strain BC in the real DD case. To avoid this uncertainty, the shape of the FLC on the left side should be checked by additional cup drawing test as showed for example in Figure 12. But even then the prediction of the critical depth is still not “robust” in a process control sense.

Figure 17. Comparison of the different FLCs in the extrapolated left range (Material: AA6016).

A “robust”, reliable prediction in the case of the very small die radii can be only achieved if the extended X-FLC concept is used. The extended concept is based on:

- FLC determination with method (FLC 3) and validated with an additional cup drawing test
- determination of the fracture line based on the thinning method
- Layer based evaluation of the strains

Figure 18 demonstrates the correct prediction of the depth as well as of the crack position for the triangle test.
Figure 18. Material AA6016. FE Simulation of triangular experiment with linear fracture criterion – dashed line (strain distribution of lower, middle and upper-layer); solid line: FLC based on MMFC-criterion, Gorji [3].

5.4. Prediction of crack limits for multilayer FUSION materials

Beside Figure 15 right for the triangle part also Figure 19 for a simple cup drawing part demonstrates again clearly how significantly the DD behaviour for the multi-layer material changes.

Figure 19. Comparison of the forming behaviour: (left) monolayer material AA6016; (right) FUSION material, Gorji [4].

The reason for the significant change of the forming behavior is not a shift of the FLC – which is more or less the same for the monolayer and FUSION-material – but the significant shift of the fracture strain for the clad material, as proven with the “thinning method” and showed in Figure 20.

Figure 20. Evaluation of the fracture strains for the core (AA6016) and the clad (AA5005) materials, where dots represent measured data based on thinning-method.

5.5. FE-model for multilayer composite materials

For the modelling of the multi-layer FUSION material, Figure 5, eleven integration points (IPs) through the thickness of the composite shell elements have been employed. 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 a total core thickness of 0.88 mm. The 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 as specified in Figure 14 and Figure 20.
Figure 21. Forming behaviour of FUSION material: FE simulation of triangular experiment with linear fracture criterion (dashed line) specifically defined for the layers (strain distribution of lower, middle and upper-layer); solid line: FLC based on MMFC-criterion, Gorji [3].

Figure 21 demonstrates, that based on the X-FLC concept, the “not failed” behavior of the FUSION material was again correctly predicted.

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 thinning method, evaluating the fracture strains on Nakajima specimens, have been used. The multi-layer failure identification was implemented into the explicit FEM code LS-Dyna. It was also shown that, in contrast to the monolayer material 6xxx, the presented FUSION material allows forming operations without failure even for small die radii.

Acknowledgements
The authors are very grateful to the CTI (The Swiss Innovation Promotion Agency) for the financial support of part of this work within the project 13082.1 PFIW-IW. Also thanks to J. Timm and E. Combaz (Novelis Switzerland SA) for providing the material and performing a part of the experiments. K. Wiegand (Daimler AG), M. Selig (AutoForm Development GmbH) and E. Müller (GOM International AG) are also gratefully acknowledged for their contribution on the project results.

References
[1] G. M. Goodwin, Application of strain analysis to sheet metal forming problems in the press shop, Soc. Of Automotive Engineering, Nr. 680093, pp. 380-387, 1968
[2] Y. Bai, T. Wierzbicki: Application of extended Mohr-Coulumb criterion to ductile fracture, Int J Fract (2010) 161:1–20
[3] M. Gorji, B. Berisha, P. Hora, F. Barlat: Modeling of localization and fracture phenomena in stress and strain space for sheet metal forming, Int J of Mater Form, DOI 10.1007/s12289-015-1242-y, 2015.
M. Gorji, Instability and fracture models to optimize the metal forming and bending crack behavior of Al-Alloy composites, Diss ETH 23066, 2015

M. Gorji, B. Berisha, N. Manopulo, P. Hora. Effect of through thickness strain distribution on shear fractur hazard and its mitigation by using multilayer aluminum sheets, J Materials Processing Technology, 232: 19-33, 2016

P. Hora, L. Tong, M. Gorji, N. Manopulo, B. Berisha: Significance of the local sheet curvature in the prediction of sheet metal forming limits by necking instabilities and cracks. Proceedings of NUMIFORM -2016.

R. Schleich, M. Sindel, M. Liewald, Investigation on the effect of curvature on forming limit prediction for aluminium sheet alloys, International Journal of Material Forming, 2:69-74, 2009

K. Isik, M. B. Silva, A.E. Tekkaya, P.A.F. Martins, Formability limits by fracture in sheet metal forming, J of Processing Technology, 214:1557-1565, 2014

P. Hora, B. Berisha, M. Gorji, N. Manopulo, A generalized approach for the prediction of necking and rupture phenomena in the sheet metal forming, IDDRG12, 79-93, 2012