A new workflow for the effective distinction between necking induced spilts and direct fracture phenomena

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Abstract. The predominant mode of failure in stamping applications is still splitting due to localized necking. This kind of failure is very effectively captured by the forming limit curve, especially if nonlinear deformation effects are modelled. With the sharp increase in low-ductility (weight efficient) materials, direct fracture phenomena (surface cracks, edge cracks, shear cracks, etc.) increasingly enter the daily industrial stamping practice, especially in follow operations. Contrary to the classical FLC analysis, there exists nowadays no industry-wide standardization for characterizing these phenomena. This drives up modelling costs and reduces the expected improvement in the overall modelling uncertainty. It therefore becomes crucial to understand and detect the circumstances in which an advanced fracture characterization is necessary, such that limited resources can be effectively allocated. The present contribution aims to propose such a workflow. Firstly a reasonable lower bound for the fracture limits is estimated based on theoretical considerations and evidence from scientific literature. This estimation is used to conduct a first analysis step which is used to categorize the process based on whether a standard modelling approach is sufficient to deliver the required accuracy. A second step of accurate fracture identification is therefore only recommended for the subset of geometries with particularly high risk. The approach is tested on data for AA6016 and DP980 from literature and validated based on published experimental results.

1. Introduction
As it is the case with all engineering activities, the primary aim of numerical simulations is the minimization of uncertainties during the design of a physical system, such that it can be realized effectively and without failure. Simulation tools provide nowadays excellent possibilities for accurately modelling very complex engineering systems and deliver an unprecedented level of accuracy. On the other hand this increased effectiveness is most of the time consumed to design increasingly complex systems in shorter times, such that the tolerance for inaccurate results is also steadily decreasing. Understanding, quantifying and managing uncertainties therefore continue to be in the primary focus of the engineering endeavour. Failure of the stamping process due to local necks or spilts, can incur significant costs during tryout and/or production and can cause disruptions in the product schedules. An accurate modeling of these phenomena, therefore receives a lot of industrial attention. As a consequence the recent scientific literature has been very prolific in this direction. This is especially the case for direct fracture phenomena such as surface cracks, edge cracks and shear

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cracks. Surprisingly, only few of the proposed approaches have made it nowadays into the industrial practice. This is primarily due to the following two reasons:

1. The predominant failure mechanism in the first drawing stage is still “failure due to localized necking” which is very well captured using a (nonlinear) FLD analysis. Direct fracture phenomena occur mostly in follow operations, which are relatively easier to optimize during tryout.

2. Experimental methods for characterizing direct fracture phenomena are not standardized; they are therefore costly and nevertheless feature relatively high uncertainty.

Both of these points limit the incentive of engineers to use direct fracture models, as the overhead required many times does not counterbalance the expected reduction in the overall uncertainty levels. An effective way for resolving this dilemma is the reliable distinction of cases which are not prone to direct fracture from those which do exhibit this risk. As the majority of stamping operations fail under localized necking, this would reduce the number of cases requiring additional modelling drastically, making the cost of the latter feasible as a whole.

2. A two-step strategy for streamlining fracture prediction

The proposed implementation of the approach introduced in the previous section is depicted in Figure 1. The first step in the analysis is the carrying out of an FEM analysis based on standard material / failure data, which have been enhanced using an estimation of the fracture limits. A preliminary analysis is thus carried out on the part, which leads to two possible outcomes. Either, fracture phenomena are irrelevant for this particular case and the classical FLD analysis is sufficient to capture failure or additional fracture modelling is necessary to improve prediction.

Clearly, the decisive component of this modelling approach is the preliminary analysis used to assess the necessity for additional modelling. A reasonable lower bound fracture (LBF) limit curve (see Figure 2) therefore needs to be estimated which effectively detects the largest majority of direct fracture cases even at the cost of occasional false positives. This way if the analysis indicates no direct fracture the user can reliably use the classical FLD for predicting failure.

2.1. FLC based estimation of fracture curves
The estimation of fracture limits is no trivial task. Direct fracture phenomena are strongly local and thus strongly dependent on the materials microstructure. There are nevertheless theoretical and heuristic considerations, which can be used to estimate a reasonable low bound fracture (LBF) curve based on four cardinal directions in the FLD. These points are equibiaxial tension (EB), plane strain (PS), uniaxial tension (UT) and pure shear (SH) as depicted in figure 2.

**Figure 2.** Limiting loading states in sheet stamping.

**Figure 3.** The ratio of eq. plastic strain at failure in shear to the same measure in uniaxial tension.

*Fracture limit in equi-biaxial loading (EB).* The starting point of the estimation is the EB loading direction. It is well-known from Nakajima experiments that fracture under this mode occurs almost immediately after necking in terms of major strain. It is therefore reasonable to assume that the localized necking major strain of the FLC will provide an acceptable lower bound for the fracture major strain as well. Note that the EB conditions as well as the UT condition are purely theoretical. Devising experiments that remain purely uniaxial or purely equi-biaxial is very challenging. In most tests carried out with sheet materials there will be an observable drift towards plane strain tension loading before fracture occurs.

2.1.1. *Fracture limit in uniaxial tension loading (UT).* The fracture limit for uniaxial tensile loading is assumed to have the same equivalent plastic strain as the EB loading. This corresponds to the assumption that fracture phenomena are essentially isotropic. Many of the popular fracture models such as Mohr-Coulomb and Hosford-Coulomb [1] are based on this assumption and will predict identical equivalent strains for UT and EB. This point will be elaborated based on the HC model which reads as follows in its simplest parametrization

\[ \bar{\sigma}_{HF} + c(\sigma_1 + \sigma_3) = b \]

(1)

where \( \bar{\sigma}_{HF} \) is the Hosford equivalent stress defined as

\[ \bar{\sigma}_{HF} = \left[ \frac{1}{2} (\sigma_1 - \sigma_2)^a + (\sigma_2 - \sigma_3)^a + (\sigma_1 - \sigma_3)^a \right]^\frac{1}{a} \]

(2)

And a is a,b and c are material parameters. Introducing the uniaxiality condition \( \sigma_2 = \sigma_3 = 0 \) in (2) and then in (1) we obtain:
\[ \sigma_1 = \frac{b}{1+c} \]  (3)

The same result is obtained by enforcing the equibiaxiality condition \((\sigma_1 = \sigma_2)\) together with the plane stress \((\sigma_3 = 0)\) assumption.

2.1.2. Fracture limit in plane strain tension (PS). To estimate the plane strain tension point we will rely on the linearity of the fracture curve in the FLD between UT and EB. A linear behaviour in this region has been reported by many authors (see e.g. [2] and [3]). The limit strain is therefore:

\[ \varepsilon_{1,PS} = \varepsilon_{1,EB} \left(1 - \frac{\varepsilon_{1,UT}-\varepsilon_{1,EB}}{\varepsilon_{2,UT}-\varepsilon_{2,EB}}\right) \]  (4)

\[ \varepsilon_{2,PS} = 0 \]  (5)

2.1.3. Fracture limit in in-plane shear (SH). The estimation of the SH point is particularly uncertain. In fact it is strongly dependent on the material. Figure 3 depicts the shear limit strains reported by various authors in the literature. It is seen that there exist strong scatter even for similar or equivalent materials. In absence of better information the only conclusion that can be drawn from Figure 3 is that the fracture limit in in-plane shear is higher than in uniaxial tension for most of commonly used materials. This means that the strain limit in uniaxial tension also provides a reasonable lower bound for the in-plane shear case.

2.1.4. Edge fracture limits (EF). Edge fracture is a phenomenon that is frequently encountered especially with high strength steels and some aluminum alloys. The limiting strains for the edge formability are primarily dependent on the blanking process and on the resulting edge condition, which is mostly unknown at the simulation stage. A viable approach is to analyze edge crack conditions for various different edge conditions such as “laser cut”, “sharp edge” and “worn edge”. Heuristics can be applied for these limits relating them to the uniaxial fracture limits. A sound experimental base is in any case recommendable.

3. Results and Discussion

The proposed approach for generating a lower bound fracture curve estimate has been applied to the results published by Pack et al. [4].

3.1. Application to AA6016

Figure 4 illustrates the LBF curve in comparison to the Forming Limit Curve, whereas figure 5 compares the LBF with the fracture envelope as published in [4], plotted in the eq. fracture strain vs. stress triaxiality diagram. It is noted that the LBF estimation always remains, as by design, below the measured fracture curve. It is furthermore seen that the plane strain point is quite accurately predicted but the remaining points feature a larger safety margin up to about 33% as for the SH point.
3.2. Application to DP980

A similar behavior can be seen in figures 6 and 7. Analogously to the AA6016 material the LBF curve for DP980 also consistently remains underneath the fracture envelope reported in [4].

3.3. Validation with AA6016

Gorji [2] proposed the use of a triangle die to test for direct fracture phenomena not captured by the FLC. He reported that fracture at the die radius was observed for a die radius of 3mm, whereas the part could be drawn flawlessly until 45mm depth with a die radius of 5mm. The procedure has been
replicated using a development version of AutoForm R8 in which the proposed LBF curve has been implemented. A damage accumulation approach of the form

\[
D = \int \frac{d\bar{\varepsilon}}{E_f(\eta)}
\]

has been used to account for path nonlinearities. For the material data and process conditions the reader is referred to the original publication.

Figures 8 and 9 respectively illustrate the results obtained for a 5mm die edge radius and 3mm die edge radius. In case of the edge radius of 5mm the LBF delivered a fracture free result. Referring to figure 1 we can then stop the analysis and avoid a deeper look into fracture phenomena. In case of figure 9, however, the results indicate that the damage accumulated towards the LBF will be critical. The simulation engineer should in this case invest additional characterization/modelling efforts and evaluate the example with a more precise fracture curve in order to avoid any fracture occurrences.

4. Conclusions

Direct fracture phenomena such as surface cracks, edge cracks and shear cracks, are increasingly entering the daily industrial stamping practice, especially with low ductility materials such as high strength steels and aluminium. The experimental characterization of the corresponding limit strains is however nowadays not completely standardized. There is a large variety of different approaches and testing equipment, which lead to significant uncertainties in the measured fracture limits published in the literature. Put differently measuring fracture limits is expensive and the results obtained show high uncertainty. This creates a strong incentive to distinguish industrial cases which fail under standard conditions (splits due to localized necking) from those which are prone to fail under direct fracture. The proposed LBF approach aims taking a step in this direction. The method is effective in separating standard cases from cases requiring complex modelling. Considering that localized necking is still the most widespread mode of failure in stamping applications, this effectively reduces the characterization efforts to a small subset of stamping applications.
5. References

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