On the way towards a comprehensive failure modelling for industrial sheet metal stamping processes

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Abstract. Sheet metal stamping processes are nowadays designed with a high level of standardization. The resulting short development cycles bring by the need for highly efficient simulation software, which are able of delivering unambiguous and reliable formability predictions. This contribution aims making a snapshot of the present state of industrial needs related to this topic and to discuss the possibility for a comprehensive failure modeling approach, able of matching the high standardization requirements. For this purpose the most common failure mechanisms in stamping applications are reviewed and discussed in the context of state of the art modelling approaches. Furthermore the overall qualities required for a comprehensive failure modelling approach in the context of stamping simulation are elucidated and discussed.

1. Introduction

Stamping simulation technology, especially in conjunction to automotive applications, has nowadays reached a very high level of maturity. Complex stamping dies are designed almost exclusively based on numerical predictions and they can be reliably manufactured and tested on tight schedules and with a high success rate. This increased confidence on numerical simulation contributes in turn to the transformation of the stamping industry itself. On the one hand die designs as well as materials get increasingly complex. Sharp edges and quick curvature changes, previously deemed unfeasible, are increasingly introduced to meet aesthetic concerns or compact space requirements. Similarly, complex material alloys are more and more preferred in the designs, in order to meet challenges coming from environmental concerns. On the other hand a raising trend towards standardization and objectivity is observed. The proof of formability as well as that of dimensional accuracy are today seen as integral parts of the die design process and as such need to be well-documented and reproducible.

As far as failure modelling is concerned, the analysis made in the previous paragraph translates to seemingly contradictory objectives. Failure modelling is required to increase in complexity in order to capture additional failure mechanisms and at the same time remain objective and reproducible. It is therefore necessary to develop a comprehensive approach, focused on the needs of the stamping industry, which covers aspects of experimental analysis, failure modelling and computational efficiency in a contiguous manner. It is clear that this can only be achieved with strong industrial-academic cooperation.
The present contribution aims going through the different failure mechanisms encountered in the stamping industry and to discuss their identification and modelling in the present state of the art. The discussion will be primarily focused on the physical effects considered and on the possibility of bringing within the context of an “Advanced Formability Analysis (AFA)” framework able of capturing the most important effects in a reliable manner. Furthermore areas which need further research will be identified and discussed.

2. Failure prediction in industrial stamping processes

2.1. Necking and Fracture

The failure mechanisms encountered in the context of sheet metal stamping can be essentially grouped in two categories: ductile fracture due to necking and fracture without necking. Although it precedes actual fracture, necking is industrially accepted as the effective formability limit of the material due to several reasons:

1. Necking leads to localized/unstable deformation which cannot be robustly controlled in production. [1]
2. Necking leads to visual defects on outer body parts and to weak spots in structural parts making them unusable
3. Numerical models react sensitively to a number of parameters (mesh size, strain rate, material properties etc.) making a reliable prediction in the post necking regime very challenging (see e.g. [2])

This means if necking occurs, the actual fracture limits of the material are no longer relevant. However, if the process properties are intrinsically stable, necking can be prevented and the material fails at the fracture limit, which is usually considerably higher than the necking limit. This situation can for example arise under severe in-plane shear deformation or under nearly pure bending loading (see Figure 1). These cases will be discussed in sections 2.2 and 2.3 respectively.

![Figure 1. Failure limits schematically depicted in the principal strain space](image_url)
This duality in formability limits is most challenging under non-proportional loading conditions. It is in fact unclear whether a material predeformed in shear or compression will neck under following stretching (at the necking limit) or directly rupture (at the fracture limit). This topic will be discussed in section 2.4.

2.2. Fracture under in-plane shear deformation
As mentioned in section 2.1, the mechanics of the stamping process can give rise to situations where the largest strains in the material are in in-plane shear. As shear deformation intrinsically preserves the sheet thickness it is not prone to localized necking. Failure thus occurs when the shear fracture limit is reached.

![Figure 2. Dependency of the fracture strain on stress triaxiality (η) and Lode parameter (ξ). Plotted according to the model description in [3]](image)

![Figure 3. FLD of an industrial example which likely experienced shear fracture. The elements marked in yellow correspond the fracture location on the drawn steel sheet, the lines depict the deformation path.](image)

Thanks to significant research efforts in the last decade, it is nowadays a well-known fact that for some sensitive sheet metals, the pure shear fracture limit can be significantly lower than the ductile fracture limit, say in uniaxial tension [3]. This publication and many others have also shown that this lower fracture limit in the low triaxiality regime is also accompanied by an increased sensitivity to the so-called Lode parameter (see Figure 2). This point is significant for two reasons:

1. It is challenging to design an experimental setup which is able of accurately measuring the limit strains in pure shear. In fact small changes in Lode parameter can significantly change the limit strains associated to this deformation state. This reflects itself as a large range in limit values reported in the literature even for the same material grades.

2. As far as stamping processes are concerned only a very limited number of industrial examples really fail in in-plane shear. In fact critical shear strains are only reached in cases which deform almost linearly in in-plane shear up to fracture (see Figure 3).

These two factors result in a relatively slow penetration of shear based failure prediction into the industrial practice. From the process developers’ viewpoint there is often no clear added value in making a priori additional measurements to characterize shear fracture modes, as these occur infrequently and there is no established standard for their testing. The real challenge in the simulation based prediction of this fracture mode lies in fact in the definition of standardized experiments able of reliably characterizing the corresponding limit strains. Efforts for industry-wide cooperation in this...
direction have been announced by Prof. Pavel Hora (ETH Zurich) in the FTF 2018 Conference in Zurich Switzerland.

2.3. The bending effect
The fact that necking depends on superimposed bending is a well-known fact since decades. This phenomenon has also received significant academic attention (see e.g. [4], [5], [6]). These methods have however not reached widespread industrial acceptance, except partially for hemming applications. The main reason behind this is that superimposed bending usually has a stabilizing effect as far as membrane instability is concerned and therefore remains on the safe side.

With the sharpening of geometrical features as well as with the shift towards high strength materials with limited ductility, a previously seldom encountered failure mode started emerging in the industrial stamping practice. In fact under severe stretch bending conditions, materials may fail on the surface although membrane strains remain below the FLC. This can be primarily attributed to the fact that the necking phenomenon initiates asymmetrically on the outer surface of the blank, leading to premature surface cracks in low ductility grades. This phenomenon has been studied by Neuhauser et al. [7] in their recent work with a DP600 alloy.

![Figure 4](image1.png)  ![Figure 5](image2.png)

**Figure 4.** Necking limit at different stretch bending conditions. (data from [7])

**Figure 5.** Punch displacement at failure for different stretch bending conditions (data from [7])

Figure 4 depicts the almost quadratic increase in the necking strain with decreasing bending radius. At first sight this looks like an improvement in formability. Figure 5 indicates however, that failure actually occurred with smaller displacements with decreasing radius. Assuming that the stretching component of the strain is proportional to the drawing depth and that the neutral axis does not change significantly, this situation cannot be explained with an increase in the membrane strains. It is in fact reasonable to assume that the surface strains led to the actual formability limits. The 3D simulation results depicted in that study and reported here in Figure 6 illustrate why despite an increase in limit strains, failure can happen prematurely. It is in fact seen that if the bending radius is small enough (2.5mm in this case), necking initiates asymmetrically on the outer layer instead of symmetrically around the membrane layer. This in turn means that the strains on the outer layer can be disproportionately higher than the membrane strains, reaching ultimately the fracture limit before membrane strains become critical. This behaviour is observed particularly with materials having low ductility both because these materials tend towards stronger through thickness strain gradients and because they tolerate less post-necking plasticity.

Another important issue closely connected to bending, is the behaviour of the material going through the drawbeads. The multiple bending/unbending which the material undergoes in these regions is superimposed with an overall stretching due to the restraint. This results in positive principal strains in
the direction of motion, which often exceed the FLC right after the drawbead. In reality however failure near the drawbeads and in the direction of motion is almost never encountered. It is known that cyclic straining increases the effective failure strains (see e.g. [8]). This is however still not a well-studied phenomenon in the range of materials and processes related to sheet metal forming. A pragmatic approach for including these effects has been proposed by [9], with successful results on a wide range of industrial examples.

![Figure 6. Schematic representation of the blank geometry around the punch in the stretch bending experiment at the last increment before structural instability. It is seen that although the blank remains stable localization is beginning on the top surface (flattening) [7]](image)

2.4. Nonlinear deformation
One of the most important challenges in failure prediction is the description of path dependence. In fact the experimental effort required to characterize arbitrary path changes grows exponentially with the number of steps considered. Volk and collaborators (see e.g. [10],[11] and [12]) have made very significant efforts in the experimental characterization and phenomenological modelling of necking under multilinear deformation. Especially the experimental base generated as such, is invaluable for predicting nonlinearity effects in the Nakajima range. Stress-based (e.g.[13]) and mixed stress-strain

![Figure 7. Pre-strain in in-plane shear followed by plane strain deformation](image)  
**Figure 7.** Pre-strain in in-plane shear followed by plane strain deformation

![Figure 8. Complex pre-strain in compression followed by plane strain deformation](image)  
**Figure 8.** Complex pre-strain in compression followed by plane strain deformation
(e.g. [14]) are also known to deliver results which are consistent with experimental findings. All of these approaches, however, are limited to nonlinearity in the Nakajima range, which mainly arise in the drawing stage. Secondary forming operations, especially if the blank is trimmed after drawing, can lead to deformation histories much more complex than the ones obtained in Nakajima range. For example nonlinearities arising from predeformation in shear or even compression are known to lead to premature failure in industrial applications. Figures 7 and 8 depict deformation paths of two industrial examples which lead to failure in reality and could not be explained by traditional methods. For such cases, it is especially of interest to understand whether failure will occur due to necking or by direct fracture. This kind of deformation histories are challenging to obtain experimentally. So there is nowadays limited information on which mechanisms are at play. This is however a very significant point in order to meet the increasing demands in accuracy arising from multi-step stamping operations.

Approaches based on “damage accumulation” have been recently proposed for considering path nonlinearity in predicting necking. These approaches naturally include deformation zones outside of the Nakajima range and can be seen as a weighted average of plastic strain over the deformation path, scaled with instantaneous, stress dependent, plastic strain limit.

\[ L = \int \frac{d\varepsilon}{\varepsilon_i(\eta, L)} \]

If the limit strain is described as the FLC (e.g. transformed to the Heigh-Westergaard space) this approach will deliver an identical prediction to the FLC for proportional loading. The ability of this kind of modelling to capture nonlinear deformation has been discussed in [15] as well as [16]. Both papers illustrate that the accumulation approach delivers consistent results with expected non-linear necking limits. Matthiasson et al. furthermore suggest that a direct comparison of the plastic strain with the momentary limit strain gives slightly better results. This partial loss of accuracy is counterbalanced by the increased robustness provided by accumulation methods. In fact direct comparison approaches rely on the stress state on the last increment. Slight changes in the process conditions can lead to changes in the stress state, which in turn can lead to wrong predictions.

2.5. The role of edge quality

The failure limits on the blank edge usually differ to the ones within the forming domain. This is primarily related to edge quality as well as deformation history resulting from cutting the blank. The overwhelming variety of possibilities in preparing blank edges makes it challenging to describe the reduced formability on the edge, based on purely theoretical considerations. There are a number of different experimental approaches for measuring limit strains, such as hole expansion tests with different punch geometries (conical, spherical, flat). In addition to the edge condition, these limit strains are also known to be dependent on the strain gradient perpendicular to the edge, as well as on the superimposed bending. These latter dependencies are also known to be strongly variable with the material type. Although the modelling possibilities in the state of the art for this kind of fracture remains limited, prediction quality is greatly improved in presence of experimental data. Similarly as in the shear fracture case, it is of utmost importance to reach an industry-wide agreement on a standardized set of tests able of covering most of the important factors.

3. Advanced formability analysis for stamping applications (AFA)

As it can be inferred from the previous section there are nowadays a large number of experimental and theoretical approaches which very successfully predict failure within the limits of their definition. The partial nature of these solutions, however, inevitably inhibits their industrial penetration. Today’s short development cycles in fact dictate clear standards on formability predictions, leaving limited room for the engineering judgement required in presence of alternative and possibly contradictory models. The industrial practice therefore still remains with the less accurate but well standardized FLC analysis.
The most viable way of enabling the increased usage of advanced modelling approaches is the definition of a central framework, which includes all relevant phenomenological effects into a unique forecast. A robust global prediction consistent with theoretical and practical expectations gains therefore priority over accurate niches.

3.1. Requirements for a comprehensive modelling approach

The considerations in the previous paragraph bring by the need to discuss the qualities which an industrially applicable and centralized failure model should possess. This discussion is independent of the actual modelling approach selected. In fact any model satisfying the following conditions will have good chances of becoming an industry standard.

3.1.1. Primum non nocere. The phrase in the heading is the Latin expression for the medical principle “First do not harm!” An overwhelming majority of stamping simulations today are made with traditional materials loaded under nearly linear deformation paths. The FLC is an experimental methodology which has an outstanding success rate under these conditions. This means that any alternative modelling approach must meet the minimal condition of being consistent with measured FLC in case of linear deformation, no bending effects and no edge influences.

3.1.2. Ability to model path nonlinearities. The modelling framework must provide the means for predicting failure in presence of nonlinear deformations at the widest possible range of loading histories. This should especially include ranges outside the Nakajima window in order to achieve accuracy in multi-step operations.

3.1.3. Ability to deal with direct fracture. The vast majority of splits in industrial applications are preceded by necking. There is however circumstances in which the material loses load carrying capacity without experiencing significant necking. In-plane shear (e.g. pure deep drawing) and pure bending (e.g. hemming) as well as strong path nonlinearity (e.g. multi-step drawing) can lead to such situations. The modelling approach should have a clear strategy to distinguish necking and fracture and to consider the corresponding experimental limits.

3.1.4. Account for the gradient across the thickness. Localization is mostly considered to be an instability effect through the whole thickness of the material. However, under stretch-bending conditions necking can be also triggered through instability on the material surface. Although the dependence of instability on the bending radius is well known, this topic did not yet reach industrial maturity, it is however necessary for a successful comprehensive formability analysis.

3.1.5. Account for edge effects. Accounting for edge quality in failure modelling is less than a trivial task. The deformation and damage history of the material during edge preparation, as well as the plastic and microstructural properties of the material can sensitively affect the deformation limits. Standardized experimental approaches are necessary for a successful inclusion of this effect into the modelling.

3.1.6. Compatibility with the underlying numerical framework. The need for failure modelling intrinsically arises from the fact that numerical methods used in industrial application cannot deliver the level of detail required to capture instability and fracture phenomena. This gap is therefore bridged with additional modelling and experimental data (e.g. the FLC). Shell elements are nowadays the primary choice for large scale simulations. A successful failure modelling approach needs therefore to be designed considering the limitations of this numerical framework.
4. Conclusions
Phenomenological modelling of localization and fracture is and remains one of the most challenging topics in solid mechanics and plasticity. This is primarily due to the fact that the modelled effects are intrinsically microstructural and thus they lead to dependencies on a large number of macroscopic quantities such as stress state, deformation history, deformation speed etc.. This puts a clear challenge on the experimental characterization for arbitrary 3D modelling approaches. However, on the bright side, stamping simulations lead to a well-defined and well-understood subset of stress and deformation states, which in turn lead to a limited number of observed fracture modes. Achieving high reliability in failure prediction is therefore a significantly more realistic goal for stamping applications. The challenge lies in developing a comprehensive understanding of all relevant mechanical/material effects and of the corresponding failure modes. Once this is achieved focused efforts must be spent in the standardized characterization of the corresponding formability limits. This should be done by keeping in mind the limitations of the underlying numerical approaches used in the calculations.

References
[1] Hora P, Berisha B, Gorji M and Manopulo N, 2012 Proceedings of IDDRG Conference 79-93
[2] Gorji M, Manopulo N, Hora P and Barlat F 2016 Int J Solids Struc 102-103 56-65
[3] Wierzbicki T, Bao Y, Lee Y-W and Bai Y 2005 Int J Mech Sci 47 719-43
[4] Hora P and Tong L 2008 Proceedings of Numisheet Conference 7 205-210
[5] Schleich R, Sindel M and Liewald M 2009 Int J Mater Form 2 69-74
[6] Kitting D, Offenheimer A, Pauli H and Till ET 2010 Int J Mater Form 3 1163-66
[7] Neuhauser FM, Terrazas O, Manopulo N, Hora P and Van Tyne C 2018 Int J Mater Form
[8] Macardet SJ and Mohr D 2015 Int J Plast 72 21-43
[9] Erürk S, Sester M and Selig M 2018 Proceedings of Forming Technology Forum 11 41-46
[10] Volk W and Suh J 2013 AIP Conference Proceedings 1567 556
[11] Jocham D, Gaber C, Böttcher O, Wiedmann P and Volk W 2017 Int J Mater Form 10:4 597-605
[12] Gaber C, Jocham D, Weiss HA, Böttcher O and Volk W 2017 Int J Mater Form 10:3 345-51
[13] Stoughton TB and Yoon JW 2012 Int J Solids Struc 49:23 3616-25
[14] Hora P, Tong L, Berisha B 2013 Int J Mater Form 6(2) 267-79
[15] Matthiasson K, Jergeus J and DuBois P 2014 Int J Mech Sci 88 175-91
[16] Pack K, Tacogne-Dejan T, Gorji M and Mohr D 2018 Int J Solids Struc 151 214-32