

# A Path Independent Forming Limit Criterion for Sheet Metal Forming Simulations

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## ABSTRACT

A new strain-based forming limit criterion is proposed to assess the localized necking failure for sheet metal forming simulations when deformation paths deviate significantly from linearity. Different from the traditional strain-based Forming Limit Diagrams (FLD) in terms of major and minor strains, the new FLD is constructed based on effective strains and material flow direction at the end of forming. This new criterion combines the advantages of stress-based FLD for its path-independence and the traditional linear strain path FLD for its easy interpretation. The proposed FLD is validated through both theoretical prediction with Marciniak-Kuczynski (M-K) model and available experimental data in literature, and its relationship with stress-based FLDs is discussed.

## INTRODUCTION

The traditional strain based Forming Limit Diagram (FLD) as pioneered by Keeler and others [1-3] has been widely used to assess localized necking in sheet metal forming process due to its straight-forwardness and convenience of measuring deformation strains either physically in forming tests or simulatively in finite element modeling. In this formulation, a single Forming Limit Curve (FLC) of in-plane limit major strain versus minor strain is served as the forming limit criterion, beyond which the sheet metal is deemed to start localization. When it was initially proposed, the concept of FLDs was based on extensive experimental studies of a variety of sheet metals under bi-axial loading conditions. Theoretical models were later proposed to explain and predict forming limits, especially on the right-hand side of FLCs where both major and minor strains are positive.

Two prevailing models are widely accepted today. One is the Marciniak-Kuczynski model (often referred as the M-K model) where an initial imperfection is assumed to exist in the sheet metal [4-5]. Localization occurs when the deformation begins to concentrate within the imperfection zone due to its loss of load-carrying balance related to the

outside sheet metal. The imperfection can be either of geometric nature such as thickness reduction, or of materials nature such as lower yield strengths. Its magnitude and distribution have to be assumed or estimated for the underlying analysis, and the conventional flow theory of plasticity with a smooth yield surface gives arise to satisfactory necking phenomena.

If no imperfections are assumed to be pre-existent in the sheet metal, the localization analysis based on the bifurcation of equilibrium equations would yield forming limit stresses in the order of elastic modulus for the right-hand-side FLCs, using flow theory of plasticity with a smooth yield surface. This would be in direct contradiction with experimental observations. To resolve the conflict, Stören and Rice [6] and Hutchinson and Neale [7] proposed the use of vertex theory of plasticity where the plastic flow does not necessarily follow the normality rule under certain circumstances, and was later further developed by Zhu *et al.* [8]. The deformation theory of plasticity is one of the simplest versions of such theory, and it does give reasonable predictions for the entire range of forming limit diagrams.

It is important to note that the Forming Limit Diagram as in its current formulation is only concerned with the strain state at the end of deformation. Neither the strain paths leading to the final deformation nor the final stress states enter the equation as long as the major and minor strains are the same. Numerical models reveal that the strain path is essentially linear in the case of experimental determination of FLD with Limiting Dome Tests; and proportional loading is always assumed for theoretical analysis with either M-K model or the Vertex model. However, numerous testing data [9-12] showed that there is no single curve in strain space that can represent the forming limit if strain paths deviate significantly from linearity, or if there is sudden change in loading directions. As shown in Fig. 1, with 7% equibiaxial pre-strain, the forming limit curve is shifted to right and down from the base FLC. It is clear that the conventional FLD is valid only in linear loading path.

In sheet metal forming operations such as deep drawing under complex loading conditions, the loading paths can deviate significantly from linearity. Furthermore, in multi-stage forming processes, such as drawing followed by flanging, the loading direction will inevitably change. In order to accurately evaluate sheet metal formability in any strain path, the analyst would need a set of FLCs corresponding to all the various strain path conditions found in the part instead of the one conventional forming limit curve. This would be an almost impossible implementation task even if every curve did not have to be obtained experimentally.

A safety margin is generally employed in industrial applications of FLDs to accommodate variations from material properties and manufacturing processes. To compensate the path dependence of the base FLD curve, a larger safety margin is usually added to ensure a conservative prediction (as shown in Fig. 2a). This approach normally works out adequately for mild steels because their high formability still leaves a relatively large formability window even after the imposition of the safety margin.

In recent years, more advanced high strength steels (AHSS) such as Dual-Phase (DP) steels have been widely used in auto part designs to reduce vehicle weight while improving fuel economy and passenger safety. One of the drawbacks of these steels is their limited formability comparing to mild steels. If a large safety margin (as shown in Fig. 2b) is again imposed on the base FLD of AHSS to assess the formability, design flexibility will be greatly limited. It is thus very beneficial to have a path-independent forming limit criterion in order to assess the real formability of a formed part and not rely on the uncertain sense of security provided by a safety margin imposed on FLD.

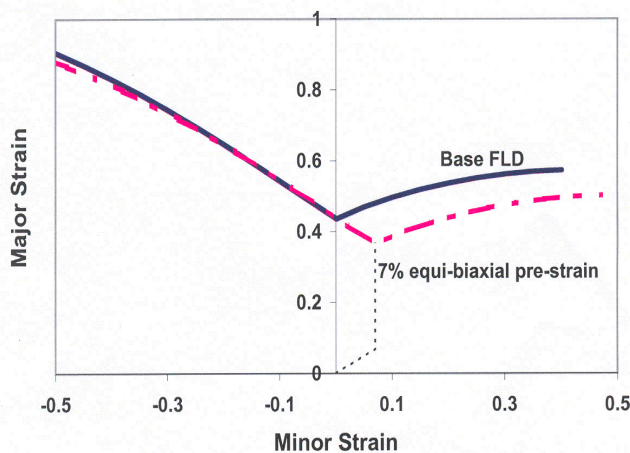
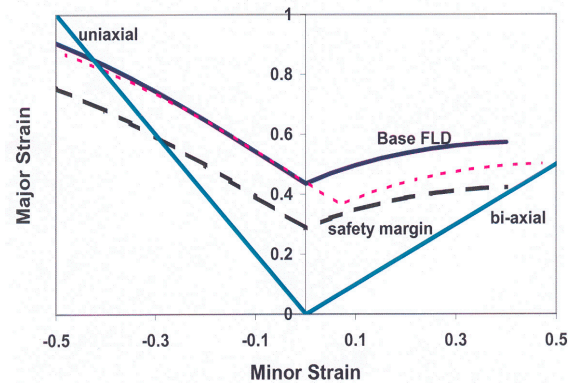
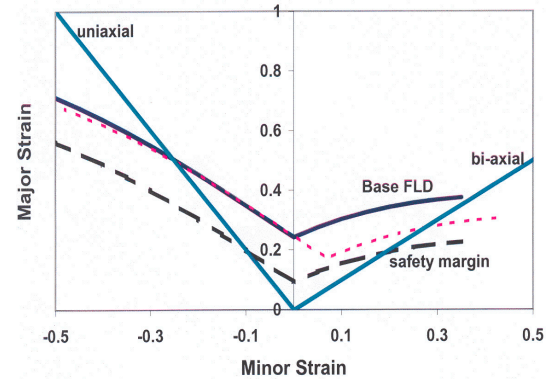


Figure 1. Path Dependent FLD Curves



(a). Mild steel FLD curve



(b). DP600 FLD curve

Figure 2. FLD Curve with Safety Margin

Recently, the Stress-Based Forming Limit Diagram (SFLD) [13-16] has received increasing attention as an alternative to the conventional strain-based FLD. It has the advantage of not depending on deformation paths, and can be conveniently converted from traditional strain-based FLDs. As articulated by Stoughton and Zhu [16], the deformation paths are naturally embedded in the final state of stresses because of the incremental nature of plastic flow. The characterization of forming limits with final stresses does not alter any theoretical or simulative aspects of sheet metal formability. Instead it should be interpreted as a change of observation platforms from which the deformation paths are no longer needed to be considered.

Despite the attractiveness of a stress-based forming limit diagram, it has so far found limited applications in industrial practice. Several factors work against its wider acceptance. Firstly the classic forming limit diagram is deeply rooted in the practical world of circle grid analysis on the shop floor. Secondly, stresses are a more abstract concept and cannot be measured in any practical way when looking at a formed part. Thirdly, the accuracy in stress prediction is less reliable than for strain, even with the tremendous advances in numerical technology for sheet metal forming over the past decade. Additionally, the use of dynamic explicit algorithms for forming simulations generates stress fluctuations due to dynamic effects and switching of contact conditions.

Finally, the sheet metal often experiences cyclic bending in addition to the dominant in-plane bi-axial deformation during the forming process. The resulting stress differential is much wider than the strain differential across the sheet metal thickness; this adds to the challenge of selecting the appropriate stress values for evaluating against stress-based FLDs.

In this paper, a new strain-based forming limit criterion is proposed to assess the localized necking failure for sheet metal forming simulations when deformation paths deviate significantly from linearity. Different from the traditional strain-based Forming Limit Diagrams (FLD) in terms of major and minor strains, the new FLD is constructed based on effective strains and material flow direction at the end of forming. This new criterion combines the path independence of the stress-based FLD and the ease of interpretation of the traditional linear strain path FLD. It is targeted for practical applications in industrial stamping simulation. The rest of the paper introduces the concept of the new FLD, followed by model validations based on available experimental data and a Marciniak-Kuczynski (M-K) analysis. The paper concludes with a discussion of the new method and its relationship with stress-based FLDs.

## DEVELOPMENT OF A PATH INDEPENDENT FLD CRITERION

The localized necking in sheet metal is a form of plastic instability. Within the framework of the plasticity theory with the associated flow rule and isotropic hardening, the deformation state of a given material point is fully determined by its current stress state if the material is under continuous plastic loading. This is the basis of the path-independent nature of the stress-based Forming Limit Diagram. In the meantime, the current deformation state can be equally represented by the size of the current yield surface and the direction of the plastic flow. This alternative representation forms the basis of our proposed forming limit criterion.

In the proposed criterion, the equivalent plastic strain  $\bar{\epsilon}^{eq}$ , which is related to the yield surface size (or the effective stress  $\bar{\sigma}_e$ ) for isotropic hardening by the material hardening behavior, is defined as the limit strain. The new forming limit criterion is described as a curve in a plot of the size of yield surface vs. the current direction of plastic flow (as shown in Fig. 3). The current flow direction  $\beta$  is defined as the ratio of incremental minor strain to the major strain, and can be expressed as:

$$\beta = \frac{d\epsilon_2}{d\epsilon_1} \quad (1)$$

It can be shown that  $\beta$  is uniquely related to the stress ratio  $\sigma_2/\sigma_1$  for associated flow rule with a homogeneous yield surface function.

The proposed forming limit criterion in its most general term can then be expressed as:

$$\bar{\epsilon}^{eq} = f(\beta; \text{Material Properties}) \quad (2a)$$

For a material obeying the power law hardening  $\sigma = K\epsilon^n$ , it reduces to

$$\bar{\epsilon}^{eq} = f(\beta; k, n, r) \quad (2b)$$

It is a relatively easy procedure to convert an empirical-based traditional FLC to the new form in Eq. (2), similar to the one for converting to a stress-based FLD. An example is illustrated in Fig. 3 for an 1.6mm DP600 steel. The equivalent strain is obtained using Hill's anisotropic yield criterion in this example:

$$\bar{\epsilon}^{eq} = \frac{1+r}{2r} \sqrt{\epsilon_{major}^2 + \epsilon_{minor}^2 + \frac{2r}{1+r} \epsilon_{major} \epsilon_{minor}} \quad (2c)$$

As with traditional FLD, the defined curve separates the condition for the onset of localized necking, under which is deemed to be safe from failure. However it is crucial to note that the new FLD, although it appears to be similar to the Keeler-Goodwin's, is now path-independent and applicable to any deformation paths, including sudden changes in loading directions during multi-stage forming.

The developed FLD is straight-forward to implement for stamping simulations. The strain results from the final two steps are required to calculate the direction of plastic flow. It shouldn't be a big burden in practice since all steps of results are available in finite element analysis.

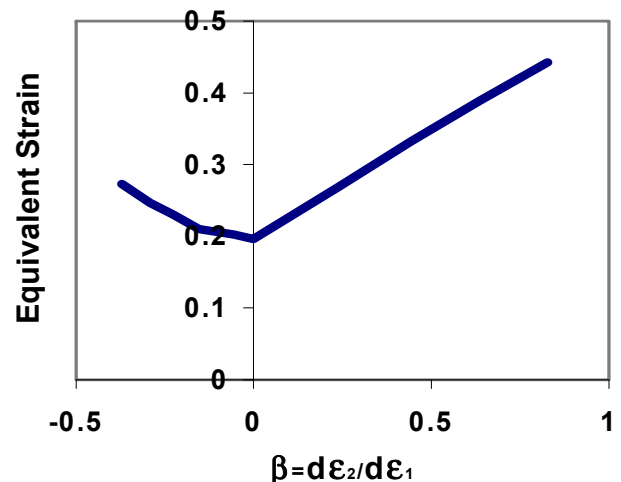


Figure 3. Proposed Path Independent FLD Criterion