



Forming limit criterion for ductile anisotropic sheets as a material property and its deformation path insensitivity, Part II: Boundary value problems



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ABSTRACT

In the common industrial thin sheet metal forming process at room temperature, in which in-homogenous deformation under the plane stress condition is typically the case, sheets are so ductile that sheet forming more often fails after abruptly severe strain localization, especially in the thinning mode. In such a case, measuring the fracture property might be impractical and an alternative criterion to measure sheet proneness to abruptly severe strain localization according to deformation modes, often dubbed as the forming limit criterion, replaces the fracture criterion to account for formability of the sheet, assuming that the criterion is applicable as a material property. However, severe strain localization is a mathematical consequence (of the boundary value problem) of the principle of linear momentum and the constitutive law; therefore not a part of material properties in principle, regardless of its sensitivity to deformation path. Nonetheless, the assumed applicability of the forming limit criterion as a material property in approximation for room temperature forming under the plane stress condition was partially validated in Part II in view of regular and modified hemispherical dome stretching and circular cup drawing tests, while its deformation path insensitive formulae were theoretically justified in Part I by examining the isotropic hardening formulation of rigid-plasticity and also theoretical forming limit models including the Considère (1885), Dorn (1947) and Hill (1952) models as well as the M–K (1967) model.

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1. Introduction

One of main objectives of engineering is to design (or optimize) forming processes. As for efficient metal forming process design in particular, computational methods are commonly applied, in which a fracture criterion is characterized as a part of material properties to predict forming failure. However, in typical industrial thin sheet metal forming processes at room temperature, forming is mainly driven by stretching under the plane stress condition (including the case of draw forming for which sheet draw-in is constrained enough) and fracture more often occurs as a result of abruptly severe strain localization in a thinning mode especially for highly ductile sheets, with a few exceptions such as the case of some advanced high strength steels including the TWIP (twinning induced plasticity) steel sheet (Chung et al., 2011a,b; Ma et al., 2010). When

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sheet splits with fracture accompanying abruptly severe strain localization, characterizing the fracture property might be impractical and the forming limit criterion to measure sheet proneness to severe strain localization according to deformation modes replaces the fracture criterion to account for sheet formability.

Now, there are two major issues to address as for the forming limit criterion: one is its relevance as a material property and the other is on its deformation path insensitive formulae. There are two approaches to address those issues: the one based on the conventional (or materials) view and the other based on the continuum/computational mechanics view. The conventional approach is based on an assumption that strain localization observed in experiments is incurred even during homogeneous deformation by physical impurities intrinsically existing in the sheet (such as non-uniform distributions of impurities, varying texture, different size and orientation of grains and so on), which were represented by the coefficient of geometric in-homogeneity for the M–K model by [Marciniak and Kuczyński \(1967\)](#). Under such an assumption, the forming limit criterion is intrinsically considered a material property, as taken by other theoretical works on forming limit diagram (FLD) such as the maximum force models including the works by [Considère \(1885\)](#), [Dorn and Thomsen \(1947\)](#), [Swift \(1952\)](#) and [Hill \(1952\)](#) as well as the works based on the bifurcation theory by [Stören and Rice \(1975\)](#). In view of the conventional approach, the deformation path insensitive formulae of the forming limit criterion can be addressed for each model individually, as done in Part I for the [Dorn and Thomsen \(1947\)](#), [Hill \(1952\)](#) and [M–K \(1967\)](#) models.

In view of continuum/computational mechanics on the other hand, while the relevance of the fracture criterion as an independent material property is acceptable without any proof, that of the forming limit criterion which is the proneness measure of the sheet to severe strain localization might need proof or extensive validations if analytical proof is unavailable. This is especially so since strain localization (whether it is severe or not) is in principle the mathematical consequence of the boundary value problem of the linear momentum principle and the constitutive law under typical forming conditions; therefore, the forming limit diagram violates the condition of the local action, which is one of three conditions required for a material property ([Malvern, 1969](#)). The relevance of the forming limit criterion as a material property has not been previously validated in view of mechanics; therefore, rather extensive and systematic validation was attempted in Part II, considering various forming conditions computationally, even though validation is still only partial. This validation effort based on computational methods is legitimate especially for the forming process design procedure, in which computational tools are applied to predict strain localization for forming failure without imposing any physical impurities (employed in the theoretical models). If the forming limit criterion is a material property in view of mechanics, the forming condition would determine only the onset location and the deformation mode near the strain localization (or critical) site, while the limit local deformation amount near the critical site would be independent of the forming condition in approximation, especially when strain localization is abruptly severe, regardless of the deformation path sensitivity of the forming limit criterion. For this validation, the β -EPS formulation was utilized as a deformation path insensitive formula for the forming limit criterion, which was validated in Part I.

For the numerical validation, the property of the DP980 sheet, whose FLD test results were shown in Part I, was considered as an exemplary property. Material properties were characterized following the common practice, involving common simplifications: the isotropic hardening of the Hill1948 yield function. Even though a more sophisticated yield function would provide better agreement with experiments, one of most popular yield functions was utilized here since agreement with experiments (therefore, the accuracy of material models used) was not the focal point. Since the strain localization is the main issue, hardening deterioration (material softening associated with micro-void growth and plastic deformation induced heat generation) was considered along with the strain rate sensitivity (but not in such a sophisticated manner as in the GTN model). The typical hardening difference measured by the simple tension and bulge tests was also ignored. As for room temperature sheet forming, as the first trial of this kind, forming conditions were limited to simple tension test and regular/modified hemispherical dome stretching tests (which are the tools to measure the forming limit criterion) as well as the circular cup drawing test, all at room temperature, in which the plastic deformation induced heat effect was ignored for simplicity. The numerical simulations were performed using the ABAQUS/EXPLICIT commercial code ([ABAQUS Inc, 2007](#)) and 3-D continuum elements, along with the Coulomb friction law.

2. Material characterization

The DP980 (Dual Phase) steel sheet (with the thickness of 1.2 mm) is one of advanced high strength steels (AHSS) developed for automotive application, having two phase composite characteristics consisting of ferrite and martensite. The strength of DP steels is attributed to the hard martensite phase, which is surrounded by the soft ferrite matrix.

2.1. Simple tension tests

Simple tension tests were carried out based on the ASTM E8M standard specimen shown in [Fig. 1](#), which was prepared by the wire cutting process. In order to consider anisotropy, simple tension tests were performed along the rolling (0°), transverse (90°), and in-between (45°) directions. Tensile speed was 0.05 mm/s, which corresponds to approximately 0.001/s in the engineering strain rate considering the gauge length of 50 mm. Typical engineering stress–engineering strain curves for each direction were plotted in [Fig. 2](#), while the measured mechanical properties of DP980 are summarized in [Table 1](#).

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