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A numerical analysis of sheet metal formability for automotive stamping applications

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Abstract

A theoretical failure model is presented for the numerical prediction of the forming limit strains of automotive sheets. The model uses the Swift's diffuse necking and Hill's localized necking concepts in describing tearing-type sheet metal failures and a computational scheme is proposed in which the failure conditions are expressed in incremental forms. The Bauschinger effect is included properly in the deformation modeling using an additive backstress form of the nonlinear-kinematic hardening rule. The necking conditions and plasticity model are transformed into a set of algebraic equations that may be applied both for proportional and non-proportional strain-controlled loadings. An iterative approach is employed in the incremental solution of algebraic equations. The formability analyses are conducted using the proposed theoretical model and the forming limit strains of two new generation auto sheets (Trip600 1.4 mm, DP980 1.15 mm) are estimated. The numerically generated FLC are compared with the experimental data and the FLC calculated with the Keeler–Brazier equation. For both steels, the model produced conservative plain–strain intercept values, FLC_0, when compared with the predictions of Keeler–Brazier equation. Also the negative minor strain part of the experimental FLD's is estimated with sufficient accuracy. For the positive minor strain side, however, the predictions are lower than both the experimental fit and the standard curve.

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1. Introduction

The increasing number of stamping parts made of lightweight materials such as high-strength steels impose several technological problems in the design and construction of the sheet metal forming tools in the automotive industries [1]. The increased springback deformation of these materials when compared with the conventional draw-quality auto steels necessitates alternate design practices in order to reduce the shape distortion during the forming and trimming processes [2]. In view of continuously reducing development costs, furthermore, the methods engineers are now expected to ensure a successful and reliable forming process design right at the first time, and this can only be achieved with an accurate assessment of the part formability early in the die-face development phase [3]. Accordingly, the methods engineer should be able to incorporate the allowable sheet metal deformations most effectively on the basis of maximum strains that can be sustained by the material without a forming failure at a feasible process condition. Thus, there is a constant need for new sets of material and formability data for these auto sheets for the control of stamping failures and compensation of springback deformations.

The sheet metal stamping failures may occur in various modes depending on the forming process, tool–blank interface conditions and material properties [3]. Restricting to tearing or splitting modes of failures only, experimental observations have indicated the strain localization as the

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prominent physical phenomenon indicating the limiting conditions for the allowable sheet metal deformations [4]. The strains that can be sustained by sheet materials prior to the onset of strain localization are, for that reason, generally referred to as the forming limit strains [5]. Keeler and Backofen [6] and Goodwin [7] introduced the concept of the forming limit diagram (FLD) in order to qualify the limiting deformation conditions of a sheet metal based on the stretch determined experimentally using grid analysis techniques. The FLD is a plot of the major and minor limit strains in the principal strain space, and became a simple and efficient tool for the stamping methods engineer in order to estimate the amount of deformation a material can withstand prior to forming failure (Fig. 1). Material subjected to proportionally increasing in-plane tension, under a plane stress state with a constant ratio of principal strains, can be safely stretched until the major strain reaches to the margin of the forming limit curve (FLC) of the material. By comparing the strains measured in the formed part to the FLC, the severity of the deformation can be assessed and process parameters such as drawbeads or lubrication regime can be designed accordingly in order to assist the forming operation. Similar to the methodology employed in the production environment, the FLC may also be used in conjunction with the FE stamping analysis in the feasibility assessment of the manufacturing process in the computer simulation environment [8].

In the past decades, the shape and distribution of FLC's for various sheet metals have been investigated for most of the highly formable low-carbon steels and for some high-strength steels and empirical expressions have been also obtained [9,10]. These data have been also used by stamping methods engineers extensively in both design and production phases. However, two technical issues arise in the practice. Firstly, there is a constant need for the adaptation of the existing material data for nonlinear loading conditions other than the prescribed proportional deformation paths for which the FLC data were mostly available. Moreover, experimental research have shown that the in-plane and out-of-plane strain components for the limiting states of the deformation may also change in magnitudes and as well as relative ratios due to the prior deformation history, the local stress state, the sheet thickness and principal directions of the anisotropy [11–13]. Consequently, sheet metal plasticity models that can describe loading–unloading or reversed loading events more accurately are required and the Bauschinger effect should be considered in the deformation response of these sheet metals [14]. Secondly, considering new generation high-strength sheet metals introduced in the recent decades, the workshop experience indicated an enhanced springback deformation that necessitates higher compensation strains. This can only be achieved by estimating the allowable deformations appropriately, and consequently, the FLC data for these materials are critically essential [15]. The FLC generation is an experimental work using special testing equipment and procedures, and may be fairly expensive and time-consuming from an industrial practice. On the other hand, the estimation of forming limit strains using a theoretical model may be useful approach in such circumstances [13,16,17]. In the recent decades, various theoretical failure models have been proposed that focus on the analysis and identification of material properties and process conditions [12–17]. In these failure models, the material damage is predicted using strain localization or a necking hypothesis in terms of stress or strain components under tensile loadings. A theoretical FLC is not a substitute of the experimental FLC, but it may be useful in the planning the formability test, in the generation of experimental data and in the investigation of the deformation conditions during the forming process. Thus, they may be employed effectively in reducing the total testing time and costs. Furthermore, these models may improve the overall productivity of computer simulations considerably during the die-face design phase especially for the cases where the material formability data is not available so far.

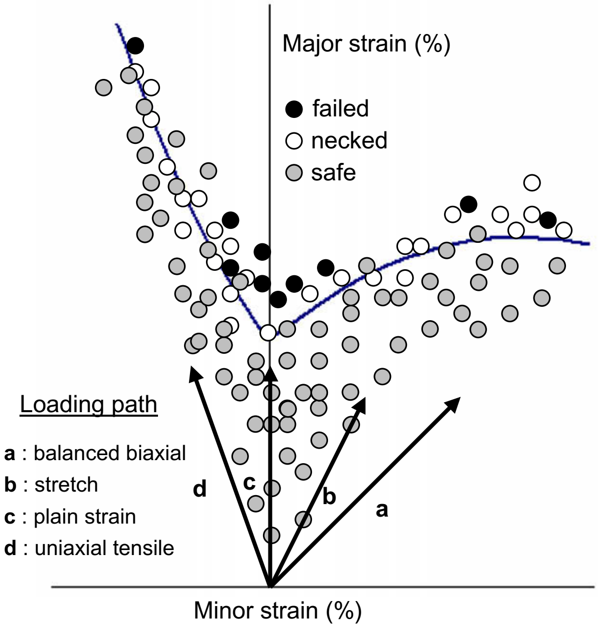

Fig. 1. A typical FLD.

In this paper, a theoretical necking model is described for the prediction of the forming limit strains of sheet metals typically used in the automotive industry and a numerical scheme is presented for the computational prediction of forming limit diagrams under plane stress deformation conditions. The mathematical model uses the Hill's orthotropic yield criterion for the description of the directional variation of yield stress and the Swift's diffusive necking and Hill's localized necking criteria are employed in the deformation–induced failure prediction of the sheet metal. The Bauschinger effect is included correctly in the deformation modeling using an additive backstress form of the nonlinear-kinematic hardening rule. The failure conditions and plasticity model are transformed into a set of algebraic equations that may be applied both for proportional and