Materials and Design 34 (2012) 32–39

Contents lists available at SciVerse ScienceDirect

Materials and Design

journal homepage: www.elsevier.com/locate/matdes

A finite element modeling and prediction of stamping formability of a dual-phase steel in cup drawing

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ARTICLE INFO

Article history:
Received 31 March 2011
Accepted 15 July 2011
Available online 3 August 2011

Keywords:
A. Ferrous metals and alloys
F. Plastic behavior
H. Failure analysis

ABSTRACT

A numerical technique is presented in order to assess formability conditions for tearing type sheet metal failures in automotive stamping applications. The proposed technique is based on the plastic instability and uses Swift's diffuse necking and Hill's localized necking concepts. Both necking models are transformed into a set of differential equations that may be applied both for proportional and non-proportional loadings and expressed an incremental form suitable for finite element (FE) analysis. Next, the numerical models are implemented into Ls-Dyna FE program and applied to predict the forming limit curve (FLC) of a high-strength dual-phase steel using in-plane proportional loadings of a single shell element. Then cup drawing processes of the same steel grade are simulated and failure heights for three square blanks are predicted. Allowable maximum punch strokes predicted with the necking models are compared with the results from square cup drawing tests under the same blankholder force. Model predictions were in accord with the experimental data and determined to be conservative for this steel grade. An investigation of cup failure heights determined with conventional technique revealed that the FE post-processing using the experimental FLC resulted in erroneous failure predictions and not conservative.

1. Introduction

The manufacture of sheet metal stamping dies requires the method engineer to ensure a successful and reliable forming process design, and a defect-free stamping part within the necessary dimensional tolerances can be the only acceptable final product of a successful sheet metal forming process. As a result, an accurate assessment of the stamping formability is essentially sought early in the die-face development phase otherwise the costs of stamping tooling may increase significantly. The stamping formability of sheet blanks are evaluated on the basis of maximum strains that can be sustained by the material without a forming failure [1], and the process conditions should be essentially optimized for the purpose of minimum blank size, less shape deviation thus higher productivity [2]. Therefore, from an industrial perspective, an effective utilization of material formability for a given tooling and loading process is a key issue that should be addressed to ensure the feasibility of the stamping process [3].

The sheet stamping failures may occur in various modes depending on the forming process, tool–blank interface conditions and material properties [4]. Considering tearing or splitting type forming failures, experimental observations have indicated the strain localization as the prominent physical phenomenon governing limiting conditions for the allowable sheet metal deformations [5]. 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. The forming limit diagram (FLD) which is a plot of the major and minor limit strains in the principal strain space is an efficient technique in this context and became a practical tool in the press shop to evaluate the limiting deformation conditions for stamping the sheet metal [6]. Keeler and Backofen [7] and Goodwin [8] described the maximum allowable major and minor limit strains by means of a forming limit curve (FLC) on the FLD plot. The shape and distribution of FLC's for various highly formable low-carbon steels have been investigated in the past decades and empirical expressions have been also obtained based on comprehensive test programs [9,10]. 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 computer environment [11]. In this approach, the FE-calculated blank deformation are post-processed in conjunction with the forming limit curve and by simply comparing the outputted strain values, the forming severity is assessed by a graphical procedure. This conventional technique has been well established in the stamping industry

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doi:10.1016/j.matdes.2011.07.038

for assessing process feasibility of low-carbon steel grades [2,3,11,12].

When it comes to stamping applications with the advanced high-strength steels (AHSS), however, technical issues arise in the practice [10,12]. These high-strength steels are relatively new to the stamping engineers, and usually a limited FLC data exists for the control of stamping failures both in the press shop applications and for formability predictions with FE analysis. Consequently, new sets of material FLC data are constantly needed for these auto sheets in order to employ the conventional FLC technique. But 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 [1,6,10]. Moreover, these light-weight steels posses an enhanced formability under stretching and drawing types deformations but also are characterized by a remarkable Bauschinger effect [10,14,15]. Path dependent deformation response and softening behavior under load-reversals bring about substantially higher springback deformations when compared with the conventional high-strength steel grades such HSLA [16]. As result, large shape distortions necessitate alternate die-face design practices and additional compensation strains in order to reduce the shape distortion during the forming and trimming processes [3,16]. In view of continuously reducing development costs, therefore, the need for theoretical modeling has been increasing for AHSS grades with no or limited material FLC data, and more detailed analysis of formability failures are essentially required in assessing the forming process, tooling design and in reducing total cost of stamping tooling [2,3,10,13,16].

In this study, a numerical technique is presented to assess formability conditions for tearing type sheet metal failures. The proposed technique based on the Swift's diffuse necking [17] and Hill's localized necking concepts [18] and expressed in an incremental form suitable for FE analysis. The necking models are implemented into Ls-Dyna FE program [19] and applied to predict the forming limit curve of an AHSS dual-phase steel. Then cup drawing processes of the same steel grade are simulated and failure heights for three square blanks are predicted. Allowable maximum punch strokes predicted with the necking models as well as conventional FLD technique are compared with the results from square cup drawing tests.

2. Theoretical modeling and failure prediction

The tearing or splitting modes of forming failures are caused by the strain localization that appears under stretching and usually manifested by the formation of a through-thickness neck on at a certain zone of the sheet metal blank. In literature, several mathematical models based on plastic instability were proposed in order to determine the amount of sheet deformation that the material can withstand prior to necking [1]. Two approaches have been usually employed in theoretical modeling the conditions for neck initiation and development. The first approach is the Swift's diffuse necking criterion which uses the concept of the maximum in-plane force condition [1,11,13–15]. Other approaches are built on the strain localization concepts known as the Hill's localized necking criterion [14,15,22] and the localization analysis introduced by Marciniak and Kuczynski [21–23]. According to Swift [17], the necking process takes place under plane stress deformation conditions and initiates when one of the tensile forces acting on a plane of the sheet metal becomes maximum under a proportional loading. In Hill's theoretical model, the sheet deformation under biaxial tensile stretching changes to plane-strain mode when necking starts and the effect of one of the in-plane forces diminishes [18]. Similar to Hill's model, the Marciniak and Kuczynski model is based on the strain localization under the plane-strain deformation, but it assumes the pre-existence of a thickness imperfection leading to necking orientation in the plane of the sheet [21]. Both necking conditions have been applied for the calculation of forming limits of various sheet metals in particular high formability low-carbon steels, and previous research showed that diffuse and localized necking criteria in conjunction with the elasto-plastic stress–strain analysis can be employed in the theoretical modeling for forming limit strain calculations [1,3,11,13–15]. Therefore, Hill's localized necking and Swift's diffuse necking criteria are chosen to estimate the forming limit curve of a high-strength dual-phase steel in this study.

2.1. Necking criteria

Swift introduced the concept of the maximum in-plane force condition considering the homogenous deformation of a sheet strip under a pure biaxial stretching loading [17]. Considering a rectangular patch of a sheet metal under plane stress conditions, the in-plane forces, F_1 and F_2, can be expressed by (Fig. 1),

$$F_1 = \sigma_{11} A_1 \tag{1}$$

$$F_2 = \sigma_{22} A_2 \tag{2}$$

where σ_{11} and σ_{22} represent the Cauchy stress components along the principal axes of the loading, and A_1 and A_2 denote the cross-section areas on which these two force components act. According to Swift's model [13–15,17,20], necking initiates when the total differentials $\mathrm{d}F_1$ and $\mathrm{d}F_2$ become zero or negative under the plane stress condition.

$$\mathrm{d}F_1 = \mathrm{d}\sigma_{11} A_1 + \sigma_{11} \mathrm{d}A_1 \leqslant 0 \tag{3}$$

$$\mathrm{d}F_2 = \mathrm{d}\sigma_{22} A_2 + \sigma_{22} \mathrm{d}A_2 \leqslant 0 \tag{4}$$

These two differential inequalities are sufficient to describe the onset of diffuse necking and represent a general framework that can be applied for any material under plane stress deformation conditions. Firat [15] expressed both inequalities in terms of principal strain and stress components considering the geometry of the rectangular patch and the following expressions were developed in conjunction with definitions of in-plane true stress and true strain components.

$$\mathrm{d}\sigma_{11} + \sigma_{11}(\mathrm{d}\varepsilon_{22} + \mathrm{d}\varepsilon_{33}) \leqslant 0 \tag{5}$$

$$\mathrm{d}\sigma_{22} + \sigma_{22}(\mathrm{d}\varepsilon_{11} + \mathrm{d}\varepsilon_{33}) \leqslant 0 \tag{6}$$

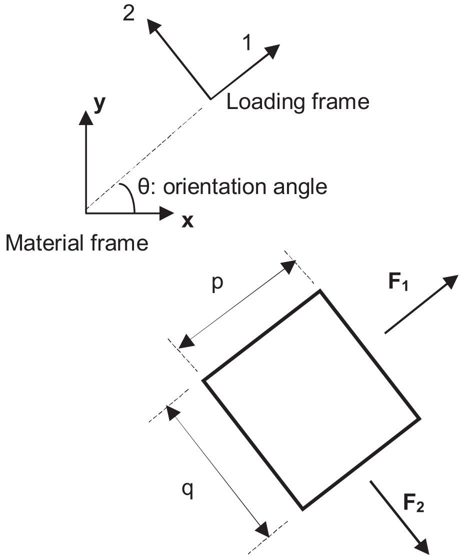

Fig. 1. A rectangular patch of sheet thickness t subject to the in-plane loads F_1 and F_2 [15].