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Analysis of plastic flow localization under strain paths changes and its coupling with finite element simulation in sheet metal forming

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ABSTRACT

Formability of sheet metal is usually assessed by the useful concept of forming limit diagrams (FLD) and forming limit curves (FLC) represent a first safety criterion for deep drawing operations. The level of FLC is strongly strain path dependent as observed by experimental and numerical results and therefore non-proportional strain paths need to be incorporated when analyzing formability of sheet metal components. Simulations using finite element method allow accurate predictions of stress and strain distributions in complex stamped parts. However, the prediction of localized necking is a difficult task and the combination of forming limit diagram analysis with finite element simulations often fail to give the right answer, if complex strain paths are not included in these predictions.

In this work a code is presented aimed at formability prediction in sheet metal forming, with a concept and structure which allows the implementation of any hardening law, yield function or constitutive equation without major difficulty. The model incorporates both approaches of the theory of plasticity, namely the phenomenological one and the physical one. Several phenomenological constitutive equations, such as, Swift hardening power law and Voce saturation hardening law, the isotropic von Mises yield criterion, the quadratic Hill yield criterion (Hill'48), the non-quadratic Hill yield criterion (Hill'79) and the Yld'96 Barlat yield criterion as well as a physics-based constitutive model accounting for the texture and strain path induced anisotropy, specifically based on the Van Houtte's anisotropic texture strain-rate plastic potential and Teodosiu and Hu microstructural hardening model, are implemented in the new model. The necking phenomenon is carried out in the framework of heterogeneous materials using the Marciniak–Kuczincki (M–K) analysis coupled with the theory of plasticity. Such code may be used to obtain forming limit curves under linear and complex strain paths as well as being used to be coupled with finite element results, as a post-processing tool, to predict occurrence of necking. Studies are presented to test and validate implemented models including some sensitivity analysis to defined variables. The influence of strain path change is presented through the consideration of several non-proportional loading sequences and theoretical results are compared with experimental ones. Also a selected sheet metal component is considered to test and validate developed code as a post-processing tool for finite element analysis and such results are compared with those obtained experimentally.

1. Introduction

Formability prediction in sheet metal forming processes is an important demand from industry, since such assessment defines the success of a stamping process. The conventional approach to assess formability uses the concept of forming limit diagrams (FLD), a concept which was firstly introduced by Keeler and Backofen (1964) and Goodwin (1968) and represents the first safety criterion for deep drawing operations. During a forming process, the strain generally increases towards the forming limit curve (FLC). When the strain reaches the FLC, a necking or fracture is supposed to occur. By comparing the strains measured in the formed part to the FLC, the severity and nature of the deformation can be assessed and process parameters such as lubricants and draw beads can be re-designed accordingly to assist the forming operation.

Although the concept of FLDs is simple, its experimental determination is not trivial, requiring a wide range of sheet forming tests. Additionally, forming limits of sheet metals are influenced by several physical factors of which the most important are material

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work hardening, strain-rate sensitivity, plastic anisotropy, the development of structural damage and strain path. It is difficult to experimentally assess the influence of each parameter individually since it is virtually impossible to change only one at a time. The experimental determination of the forming limits in sheet metal forming processes is not only tedious and expensive but also nearly impossible, since the strain paths of material points are quite non-linear and distinguished from each other. Therefore, the theoretical analysis of plastic instability and flow localization may supply relevant information to prevent the failure on the sheet metal forming process, to examine the influence of each parameter on the necking occurrence and to improve the press performance. An extensive effort has been devoted to the development of mathematical models capable of accurately predicting the plastic flow localization of sheet metal forming processes.

A large number of different theoretical approaches have been proposed to explain the localized necking in biaxial tensile fields and may be differentiated in two broad theoretical frameworks: the bifurcation analysis proposed by Hill (1952) and the localization analysis proposed by Marciniak and Kuczynski (1967). With the assumption that the onset of failure, or discontinuity of stress and velocity, leads to localized necking, Hill (1952) was the first who proposed a general criterion for localized necking in thin sheets under plane stress states. The proposed linear method is based on the plastic instability of homogeneous sheet metals and describes the initiation of localized band of straining in an otherwise uniform sheet, in order to obtain an explicit expression for predicting the limit strains. Hill observed that, during uniform deformation of a sheet, a localized sheet zone can develop along the zero-extension direction, specifically when the plastic work increment within the zone becomes less than the one for uniform deformation. Also, Hill's analysis predicts that the localized necking cannot form under stretching conditions when the strain ratio is positive, predicting only localized plastic deformation in the negative minor strain region. To compute the entire FLD, Storen and Rice (1975) incorporated the J2 deformation theory of plasticity, which is a simplified model of the corner theory, into the classical bifurcation analysis. They postulated that localized necking is due to the development of a corner on the yield surface. Therefore there is no theoretical restriction to localized necking and prediction can be performed over the entire range of the FLD. Another approach of necking description was proposed by Marciniak and Kuczynski (1967). Their mathematical model for theoretical determination of FLDs was the first realistic model and it supposes an infinite sheet metal containing a region of local imperfection where heterogeneous plastic flow develops and localizes. Hutchinson and Neale (1978) extended Marciniak–Kuczynski theory using a J2 deformation theory. Therefore, the left and right hand sides of the forming limit diagram can be calculated by M–K analysis.

A lot research work have shown that the predicted forming limit strains using M–K analysis depend on several factors, such as the yield criteria and material anisotropy, the material hardening, the material texture and microstructure and the strain paths.

The implementation of different yield criteria in the M–K model has been long tested by several authors. Parmar and Mellor (1978) investigated the dependence of limit strains on the material anisotropy based on the M–K method and non-quadratic Hill's 1979-yield function. Neale and Chater (1980) examined the combined effects of material strain-rate sensitivity and anisotropy on sheet necking and noticed a substantial effect of material strain-rate dependence. Later, Gotoh (1985) has had a relevant contribution on the development of the Stören and Rice method by using an original yield condition expressed as a polynomial function of fourth degree. Bassani et al. (1989) showed that necking strains and forming limit curves are strongly dependent on the shape of the anisotropic yield surface, for both flow and deformation constitutive theories. Banabic (1996) presented the use of a recently introduced yield criterion by Hill (1993) and studied the influence of different materials parameters upon FLD's. Better predictions are achieved when the yield surface is modeled with a polycrystalline plasticity model (Barlat, 1987a; Barlat and Richmond, 1987b) like the Bishop and Hill model (1951). In 1997, Hiwatashi et al. (1998) developed a mixed-hardening model where the shape of yield loci is generated from the texture using the Houte model (1995) whereas the isotropic and kinematic hardening is associated with the dislocation structure, using the Teodosiu and Hu model (1995). The mixed-hardening model, which predicts the transient hardening, provides the forming limit predictions that reflected experimental tendencies, which cannot be predicted by isotropic hardening models. A general result is that the predicted limit strains tend to strongly depend on the constitutive law incorporated in the analysis. The use of an appropriate yield function that describes analytically the plastic behavior of orthotropic metals allows to a better prediction of limit strains, thus giving a better shape and position of FLDs. In the last few years many new constitutive equations whose review can be found in the paper (Banabic, 2000), were proposed in order to have a best description of plastic behavior of isotropic and anisotropic materials.

This paper presents a developed code aimed at formability prediction in sheet metal forming with a concept and structure which allows the implementation of any hardening law, yield function or constitutive equation without major difficulty. The necking phenomenon is carried out in the framework of heterogeneous materials using the Marciniak–Kuczynski analysis coupled with the theory of plasticity. Such code may be used to obtain forming limit curves under linear and complex strain paths as well as being used to be coupled with finite element results, as a post-processing tool, to predict occurrence of necking. The developments concerning prediction of FLC's have been reported by the authors in previous works, where such simulations emphasized the influence of multiple variables, such as thickness, hardening, strain-rate sensitivity, as well as the important influence of strain path changes in the phenomena of onset of necking. Butuc et al. (2002a) used a more flexible mathematical method, which was applied to M–K theory to develop a general code for FLDs prediction in monotonic and two-stage strain paths. Also, Butuc et al. (2002b) presented a study by comparing different yield criteria (Yld'96/BBC2000) and showed a good correlation between experiments and computed FLD's using M–K model. Later, Butuc et al. (2003) have shown a successful correlation was observed between the AA 6000 series experimental FLDs and the computed limit strains, when the shape of yield locus was described by Yld'96 criterion and the hardening law represented by Voce equation. In these models, anisotropy was mainly characterized using different yield criteria such as Hill'48, Hill'79 and Yld'96. Additional developments of the code have been reported by the authors (Barata Da Rocha et al., 2007) to state its capability of predicting failure in industrial components, as a post-processing tool, based on results from numerical simulation (FE modelling). This paper intends to integrate and resume the current capabilities of the code concerning FLD calculation and well as a tool for failure prediction in industrial components and gives additional and extended details of the post-processing method of predicting failure in stamped parts. Currently, the code incorporates both approaches of the theory of plasticity, namely the phenomenological one and the physical one. Several phenomenological constitutive equations, such as, Swift hardening power law and Voce saturation hardening law, the isotropic von Mises yield criterion, the quadratic Hill yield criterion (Hill'48), the non-quadratic Hill yield criterion (Hill'79) and the Yld'96 Barlat yield criterion as well as a physics-based constitutive model accounting for the texture and strain path induced anisotropy, specifically based on the Van Houtte's anisotropic texture strain-rate plastic potential and Teodosiu and