International Journal of Plasticity 75 (2015) 189–203

Contents lists available at ScienceDirect

International Journal of Plasticity

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

An extended Modified Maximum Force Criterion for the prediction of localized necking under non-proportional loading

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ARTICLE INFO

Article history:
Received 22 August 2014
Received in revised form 1 February 2015
Available online 20 February 2015

Keywords:
A. Ductility
A. Cutting and forming
B. Cyclic loading
C. Stability and bifurcation
MMFC

ABSTRACT

Strain localization is one of the main sources of failure in sheet forming processes. State of the art forming limit curves allow the prediction of localization for linear strain paths but fall short in case of non-proportional loading. The aim of this contribution is to revisit the Modified Maximum Force Criterion (MMFC) and extend it to accommodate distortional hardening models. This is accomplished by uncoupling its formulation from any particular yield function and thus enabling its use as a generic framework for the prediction of forming limits under arbitrary loading conditions. Furthermore a novel approach is proposed for considering strain rate sensitivity, which substantially improves the predictive capabilities of the model under plane strain tension conditions. The method is applied to steel and aluminum materials and the role of phenomena such as Bauschinger effect, latent hardening and cross-loading contraction on localization are discussed.

1. Introduction

Prediction of localized necking in sheet metal forming processes is of utmost industrial relevance. This is on the one hand because localization occurs shortly before fracture. On the other hand, even if the part remains integral during production, necking constitutes a clearly recognizable visual defect as well as a structural weakness and thus leads to the rejection of the products. The prediction method which finds widespread acceptance in industry is the experimental determination of the forming limit curves (FLC) as originally suggested by Keeler (1966) and Goodwin (1968). These can be obtained by executing Nakajima tests which deliver the strain limit under proportional loading for different loading conditions. The results obtained are, however, bound with considerable uncertainty. This is on the one hand due to the nature of localized deformation regime, which is unstable and thus sensitive to inhomogeneities. On the other hand, even with modern digital image correlation (DIC) techniques, there is strong human involvement in the evaluation procedure, which unavoidably leads to scatter.

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http://dx.doi.org/10.1016/j.ijplas.2015.02.003
0749-6419/

Despite the associated uncertainties, experimental FLC prediction still remains the most reliable way of predicting localization. However, the high overhead required for the experiments, historically spurned the search for theoretical prediction methods. One of the best known approaches for predicting localized necking is the model proposed by Marciniak and collaborators (Marciniak and Kuczyski, 1967; Marciniak et al., 1973). The latter postulates that deformation concentrates in a narrow band due to an assumed inhomogeneity in the thickness. The M–K theory has later been extended by Hutchinson and Neale (1978) who introduced a J_2 flow theory into the model. Based on the latter work, Barata da Rocha and coworkers studied the effect of non-proportional loading and successfully predicted the increased stability under uniaxial tension followed by biaxial tesion as well as the reduced formability in the inverse case (Barata da Rocha and Jalinier, 1984; Barata da Rocha et al., 1985). The model has been later used by Barlat (1987) in conjunction to anisotropic yield loci, in order to discuss the role of plastic anisotropy on the onset of necking. The importance of the material texture has been furthermore stressed by Hiwatashi et al. (1998), who additionally combined the M–K approach to a constitutive model able of taking Bauschinger effect, transient hardening and cross hardening into account. This topic has been further treated in (van Houtte, 2005) where good accordance with experimental results could be obtained using a strain based texture evolution approach. A more comprehensive analysis which studied a large number of constitutive approaches in the context of the M–K model has been published more recently again by Barata da Rocha et al. (2009). Particular attention is paid in this work to the application of the methodology in the FEM framework. The M–K approach is also receiving substantial attention in the recent literature. For example Eyckens et al. studied the effect of the through thickness shear on localization (Eyckens et al., 2009, 2011). A generalized FLD approach has been proposed by Allwood and Shouler (2009), which removed the limitation of the M–K model to plane stress conditions. Furthermore the effect of damage evolution on localization has been discussed by Haddag et al. (2009). Crystal plasticity based approaches has been adopted by Asaro and Needleman (1985), Neil and Agnew (2009) and Franz et al. (2013) to predict necking phenomena.

Another theoretical approach is the one proposed by Hora et al. (1996, 2013), which states that once the force maximum is reached, the loading path gradually evolves towards plane strain, where actual localization occurs. Different features of the MMFC model have been investigated in a series of later publications, such as coupling with crack propagation models (Hora et al., 2003), transformation induced plasticity and temperature effects (Krauer et al., 2007), influence of curvature and thickness (Hora and Tong, 2008) and especially the eMMFC model (Hora and Tong, 2006) which delivered better match with experiments and only required the calibration of one parameter. The different MMFC versions have also received attention in the recent literature. Aretz (2004) discussed numerical issues about the model, concluding that it has a singularity in case straight line segments exist in the considered yield function. Although this statement is plausible, the source of the singularity does not lie in the MMFC model but in the yield locus description. In fact linear segments of the yield locus do not allow for a one to one relationship between the incremental strain and stress tensors. This is a generic problem affecting any method based on the associative flow rule. In a study of Banabic et al. (2005) the MMFC has been compared to other methods used to predict formability of sheets. A new formulation of the MMFC method proposing two additional calibration constants has later been published by Paraianu et al. (2010). A comprehensive review of the different models used for formability prediction of sheet metals can be found in (Banabic et al., 2010) and (Abed-Meraim et al., 2014).

The special case of predicting forming limits for sheets subject to non-proportional loading is also well studied in the recent literature. Stoughton and Yoon (2011) proposed a stress based formability criterion to overcome path dependence of strain based methods. A similar method was used by Carr et al. (2013) who derived a forming limit stress diagram from experimental FLCs. A metamodel based approach has been introduced by Volk et al. (2012); Volk and Suh (2013), who devised a methodology for approximating the results of nonlinear tension experiments and storing these into surrogate models. Chung et al. proposed using the effective strain in formulating maximum force as well as Marciniak and Kucinsky type models in order to derive path insensitive formulas for formability prediction (Chung, 2013; Chung et al., 2014a, b). A failure surface in function of the loading mode and prestrain level has been proposed by Werber et al. (2013), who conducted nonlinear straining experiments in order to identify the surface parameters. Ductile fracture criteria have been used for the prediction of forming limits under non-proportional loading by Zhalehfar et al. (2013).

2. Modified Maximum Force Criterion

The MMFC criterion, as the name suggests, is based on the well known maximum force criterion proposed by Swift (1952), which reads:

$$\frac{d\sigma_1}{d\varepsilon_1} = \sigma_1 \tag{1}$$

In fact, when (under plane stress, tensile dominant loading) this condition holds, the work hardening of the material can no longer compensate for the reduction in the section area and the diffuse necking process starts. Most of the materials can be strained considerably further before actual localized necking occurs, which makes this criterion too conservative for the detection of the latter. The modification proposed by Hora et al., bases on the fact that no matter what loading condition at the point of diffuse necking is, localization will occur in plane strain. This means that the deformation path, represented by the incremental strain ratio $\beta = \Delta\varepsilon_2/\Delta\varepsilon_1$ will gradually decrease and ultimately vanish right before the onset of localized necking. The MMFC criterion is thus written as: