International Journal of Plasticity 25 (2009) 2249–2268

Contents lists available at ScienceDirect

International Journal of Plasticity

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

Marciniak–Kuczynski type modelling of the effect of Through-Thickness Shear on the forming limits of sheet metal

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ARTICLE INFO

Article history:
Received 23 October 2008
Received in final revised form 26 January 2009
Available online 10 February 2009

Keywords:
(A) Fracture mechanisms
(B) Metallic material
(B) Plates
(C) Stability and bifurcation
Forming Limit Curve

ABSTRACT

The Marciniak–Kuczynski (MK) forming limit model is extended in order to predict localized necking in sheet metal forming operations in which Through-Thickness Shear (TTS), also known as out-of-plane shear, occurs. An example of such a forming operation is Single Point Incremental Forming. The Forming Limit Diagram (FLD) of a purely plastic, isotropic hardening material with von Mises yield locus is discussed, for monotonic deformation paths that include TTS. If TTS is present in the plane containing the critical groove direction in the MK model, it is seen that formability is increased for all in-plane strain modes, except equibiaxial stretching. The increase in formability due to TTS is explained through a detailed study of some selected deformation modes. The underlying mechanism is a change of the stress mode in the groove that results in a delay of the onset of localized necking.

1. Introduction

The Marciniak–Kuczynski (MK) type of model is widely used as a framework to develop models for the prediction of localized necking in sheet metal forming, though it is by no means the only model. Other types include the bifurcation type of model, see e.g. Hashiguchi and Protasov (2004), and the perturbation type of model, as in Boudeau et al. (1998).

Since the original paper of Marciniak and Kuczynski (1967), understanding of the localized necking phenomenon has greatly advanced. In the original paper, the existence of an initial groove with diminished thickness, of infinite length and oriented along the minor strain direction, was assumed in order to predict the forming limit of monotonic strain paths in the right-hand side of the Forming

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0749-6419/$ - see front matter
doi:10.1016/j.ijplas.2009.02.002

Limit Diagram (FLD). Later on, as in Hutchinson and Neale (1977a), it was extended to cover the whole range of the FLD by considering all possible initial orientations of the groove and retaining the lowest value of the major strain at the onset of localized necking as the limit strain. In a sense, the groove in the MK model is an idealized form of the inhomogeneous nature of plastic properties of the sheet, and from consideration of a large number of groove orientations, the weakest direction in the sheet with respect to localized necking resistance can be retrieved.

The accuracy in the right-hand side of the FLD has increased over the years by improvements of the constitutive behaviour. It was recognized, e.g. in Hutchinson and Neale (1977b), that taking strain-rate sensitivity into account shifts the Forming Limit Curve (FLC) to higher major strain levels in better accordance with experiments. This effect is even significant for materials with low strain-rate sensitivity, such as steels (Ghosh, 1977). The use of more realistic yield loci results in an improved shape of the predicted FLC in the right-hand side of the FLD. In Barlat (1989), different isotropic yield loci were used in an MK model: i.e. the polycrystalline Taylor–Bisshop–Hill yield loci for random crystallographic texture, using fcc or bcc slip systems. They produce FLCs that are quite realistic compared to the Tresca and von Mises yield loci which result in gross under- or overestimation, respectively. The significance of the yield surface shape for the right-hand side of the FLD is further explored in Lian et al. (1989), where it is shown that the FLC shape is strongly related to the yield surface shape between plane strain deformation and equibiaxial stretching. The stress increase during the strain path change towards plane strain of the groove in the MK model results in a delay in the onset of necking in the right-hand side of the FLD. These authors proposed the 'yield surface shape hardening diagram', which is derived from the yield locus, to assess the delay of necking in this region of the FLD. In Yao and Cao (2002), mixed isotropic–kinematic material hardening is considered within an MK analysis. It is shown that forming limits are also sensitive to anisotropic hardening, modelled by the kinematic shift of the yield locus.

In recent years, physical plasticity models have been used within the MK framework, e.g. in Knockaert et al. (2002), which uses a rate-independent polycrystal plasticity model with Taylor homogenization scheme. Such material modelling allows taking the evolution of the crystallographic texture during forming into account, and is a further improvement in the accuracy of FLC predictions. Different studies on this topic indicate that it depends on the initial texture whether or not formability is influenced by texture evolution. In Inal et al. (2005), employing a rate-sensitive elasto-plastic polycrystal plasticity model, the effect of texture evolution on formability was found to be negligible, while in Tóth et al. (1996), the study of the formability of three aluminium textures shows the tendency to equalize the forming limits of the different textures and lower them when texture development is considered. This last study uses the rate insensitive Taylor approach of polycrystal plasticity. The effect of the cube texture component in aluminium is studied with a rate-dependent plasticity model in Wu et al. (2004), where it was found that the spread around the ideal texture component determines whether or not formability is influenced by texture evolution under equibiaxial stretching. Signorelli et al. (2009) use a viscoplastic self-consistent (VPSC) polycrystal material model within the MK framework. It is demonstrated that the different textural evolutions associated with a difference in initial texture, can shift the right-hand side of the predicted FLC up- or downwards to a significant extent. It is also seen that a higher grain aspect ratio in the VPSC model reduces limit strains in the right-hand side of the FLD. In Neil and Agnew (2009), dislocation-based plasticity as well as mechanical twinning of an Mg alloy (hcp) is considered, at different elevated temperatures, within the framework of a VPSC material model. It is found that twinning can promote the resistance to localized necking.

Although the FLD is a widely spread tool in press shop practice, it has its limitations. In its original form, it can not be used for formability predictions under non-monotonic loading conditions, for sheets which are bent during forming, and for sheets subjected to non-zero stresses normal to the sheet plane during forming. Insights in these limitations have been established in the past through the MK model concept, as discussed next.

In an extensive study by Barata da Rocha (1989), it is found that under equibiaxial stretching followed by uniaxial tension, formability is dramatically lower compared to the monotonic FLD, while much higher limit strains are obtained under uniaxial tension followed by equibiaxial stretching. As reported in this paper, the same trends are also found in experimental investigations. In Hiwatashi et al. (1998), the effect of anisotropic hardening at strain path changes (due to dislocation substructure