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Computational analysis of stress-based forming limit curves

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Abstract

This article, through computational analyses, examines the validity of using the stress-based and extended stress-based forming limit curves to predict the onset of necking during proportional loading of sheet metal. To this end, a model material consisting of a homogeneous zone and a zone that has voids (material inhomogeneity) is proposed and used to simulate necking under plane strain and uni-axial stress load paths. Results of the in-plane loading computations are used to construct a strain-based formability limit curve for the model material. This limit curve is transformed into principal stress space using the procedure due to Stoughton [Stoughton, T.B., 2000. A general forming limit criterion for sheet metal forming. International Journal of Mechanical Sciences 42, 1–27]. The stress-based limit curve is then transformed into equivalent stress and mean stress space to obtain an Extended Stress-Based Limit Curve (XSFLC). When subjected to three-dimensional loading, the model material is observed to display a variety of responses. From these responses, a criterion for the applicability of the XSFLC to predict the onset of necking in the model material when it is subjected to three-dimensional loading is obtained. In the context of straight tube hydroforming, to provide support for the use of the XSFLC, it is demonstrated that the criterion is satisfied.

Keywords: Forming; Finite elements; Stress-based formability

1. Introduction

It is well known that the strain-based forming limit curve (ϵFLC), introduced by Keeler and Backofen (1963) and Goodwin (1968), does not predict the formability limit (the onset of necking) when the sheet metal is subjected to non-linear strain paths. For example, Ghosh and Laukonis (1976) observed that the ϵFLC of pre-strained steel sheet shifted and changed shape when compared with the ϵFLC of the as-received sheet. Similar results have been reported by Graf and Hosford (1993) for an alumimun alloy sheet. To develop a forming limit criterion for non-linear strain paths, Stoughton (2000) introduced a stress-based approach in which the ϵFLC was transformed into principal stress space with appropriate constitutive assumptions. He showed that the ϵFLC of the as-received sheet and the pre-strained sheet mapped into nearly coincidental

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curves in principal strain space. That is, within the scope of the constitutive assumptions, there exists a single curve in principal stress space that represents the formability limit of the sheet. The stress-based approach, therefore, appears to be particularly attractive to predict the formability of sheet metal in forming processes that subject the sheet to non-linear strain paths.

However, both the ϵFLC and the σFLC are measured and derived, respectively, for plane stress loading conditions. In some metal forming processes, such as hydroforming and stretch flange forming, the onset of necking occurs under loading conditions that are not plane stress. Simha et al. (2007) show, using finite element computations, that the onset of necking during hydroforming occurs under three-dimensional loading. The sheet metal in this forming operation starts to neck at locations wherein, in addition to the in-plane loads, there is a through-thickness component of compressive stress. Gotoh et al. (1995) and Smith et al. (2003) have proposed analytical modifications to the ϵFLC to account for the presence of through-thickness components during forming. The validity of using such limit curves in forming processes has not been studied.

Therefore, when the neck forms under three-dimensional loading, a formability criterion that can predict the limit of formability under non-linear strain paths, as well as three-dimensional load paths, is required. To this end, we have proposed a novel stress-based formability limit approach that utilizes the ϵFLC and derives an extended stress-based formability curve (XSFLC), Simha et al. (2007).

Fig. 1 presents schematics of the ϵFLC, the σFLC and the XSFLC for the as-received sheet. Load paths that corresponds to uni-axial stress, plane strain and bi-axial loading are also shown. (The term load path is used interchangeably to denote load paths in principal strain, principal stress, and XSFLC space. The particular space being referenced will be clear depending on the context in which the term is used). These load paths are linear in strain space and are non-linear in principal stress and invariant space, but they are shown as straight lines in the figure for the purpose of illustration. In order to transform the ϵFLC into the σFLC, for simplicity, J_2 flow theory and isotropic hardening was assumed in our earlier report Simha et al. (2007). In principle, more sophisticated constitutive descriptions can be used to obtain the σFLC (Stoughton, 2000; Stoughton and Yoon, 2005). The XSFLC is obtained by transforming the principal stresses of the σFLC through the expressions

$$\Sigma_{\mathrm{eq}} = \sqrt{\sigma_1^2 + \sigma_2^2 - \sigma_1\sigma_2} \quad \text{and} \quad \Sigma_{\mathrm{hyd}} = \frac{\sigma_1 + \sigma_2}{3}, \tag{1}$$

where Σ_{eq} is the equivalent stress, and Σ_{hyd} the mean stress, which is assumed to be positive in tension. In sheet metal forming operations, as long as the plane stress approximation is valid, with a knowledge of the load path in principal stress space, the σFLC can be used to predict the onset of necking. Though the XSFLC can be used for predicting the onset of necking under in-plane loading, it is intended for processes wherein the neck forms under three-dimensional loading conditions and for which the neck forms under mean stress states spanned by the XSFLC (Simha et al., 2007). This extension possible because the variables, mean stress and equivalent stress can be used to describe three-dimensional load paths. There is, however, an important consideration before the XSFLC can be used.

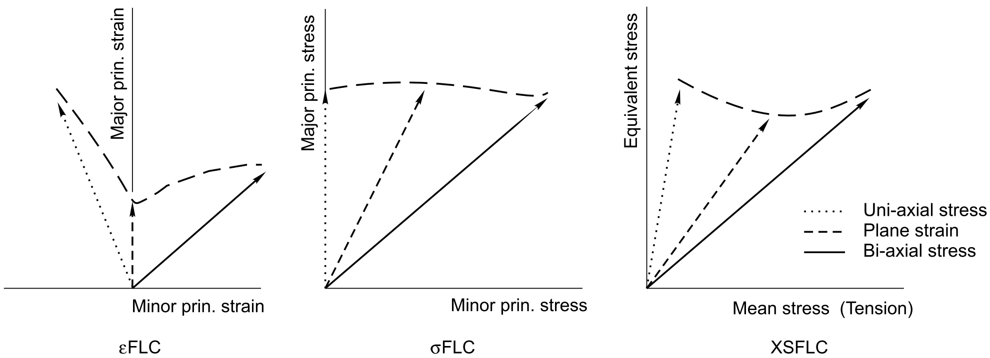

Fig. 1. Schematics of the ϵFLC, σFLC and the XSFLC. The paths are drawn as straight lines for the purpose of illustration.