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Analysis of the extended stress-based forming limit curve considering the effects of strain path and through-thickness normal stress

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ABSTRACT

In this study, an approach based on the modified Marciniak–Kuczynski (M–K) method for computation of an extended stress-based forming limit curve (FLC) is presented. The extended stress-based FLC is built based on equivalent plastic stress versus mean stress. This curve has some advantages in comparison with the conventional FLC. This new criterion is much more strain path independent than the conventional FLC. The effect of strain path on the predicted extended stress-based FLC is reexamined. For this purpose, two types of pre-straining on the sheet metal have been loaded. Moreover, the plane stress state assumption is not adopted in the current study. The influence of a through-thickness compressive normal stress is also investigated theoretically. The verifications of the theoretical FLCs are performed by using some available published experimental data.

1. Introduction

A conventional Forming Limit Curve (FLC) in terms of major and minor strains is applied to predict necking in sheet metal forming processes [1]. This curve can be obtained experimentally and numerically [2].

Marciniak and Kuczynski [3] presented the most well-known method (e.g., the M–K method) to calculate sheet metal forming limits. They assumed that an initial inhomogeneity in the thickness of the material was existent, and they assessed plastic instability phenomenon using two-zone model. In literature, there are many researches (e.g., see [4–7]) which used the M–K method to obtain the FLC.

Panich et al. [4] presented experimental and numerical analyses of Forming Limit Diagram (FLD) and Forming Limit Stress Diagram (FLSD) for two Advanced High Strength Steel (AHSS) sheets grade DP780 and TRIP780. In this study, initially, the forming limit curves were experimentally determined by means of the Nakazima forming test. Subsequently, analytical calculations of both FLD and FLSD were carried out based on the M–K model. Additionally, the FLSDs were calculated using the experimental FLD data for both investigated steels. Different yield criteria, namely, von Mises, Hill's 48, and Barlat2000 (Yld2000-2d) were applied for describing plastic flow behavior of the AHS steels. Both Swift and modified Voce strain hardening laws were taken into account. Hereby, influences of the constitutive yield models on the numerically determined FLDs and FLSDs were studied regarding to those resulted from the experimental data. The obtained stress based forming limits were significantly affected by the yield criterion and hardening model. It was found that the forming limit curves calculated by the combination of the Yld2000-2d yield criterion and Swift hardening law were in better agreement with the experimental curves. Finally, hole expansion tests were conducted in order to verify the different failure criteria. It was shown that the stress based forming limit curves could more precisely describe the formability behavior of both high strength steel sheets than the strain based forming limit curves.

Assempour et al. [5] presented a methodology for prediction of the FLSD and reexamine the effect of strain path on prediction of FLSD. The methodology is based on the M–K model. For calculation of sheet metal limiting strains and stresses, a numerical approach using the Modified Newton–Raphson with globally convergence method has been used. The evaluation of the theoretical results has been performed by using the published experimental data for ST12 low carbon steel alloy.

Butuc et al. [6] developed a detailed study on the stress-based forming limit criterion (FLSD) during linear and complex strain paths. The calculation of stress-based forming limits based on experimental strain data was performed by using the method proposed by Stoughton [7]. By applying several combinations of

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Nomenclature

f_0	initial imperfection factor or fractional ratio
fld_0	major strain in plane strain state
d_0	initial grain size (mm)
K	strength coefficient (MPa)
m	strain rate sensitivity exponent
n	strain hardening exponent
r	normal anisotropy coefficient
R_0	initial surface roughness (mm)
t	material thickness (mm)
Y	yield stress value (MPa)
α	in-plane principal stresses ratio (σ_2/σ_1)
$\dot{\bar{\varepsilon}}$	rate of effective plastic strain
$\bar{\varepsilon}$	effective plastic strain
ε_0	pre-strain value
$d\bar{\varepsilon}$	effective plastic strain increment
$d\varepsilon$	strain increment tensor
$d\varepsilon_1$, $d\varepsilon_2$, $d\varepsilon_3$	strain increments in the material coordinates
$d\varepsilon_n$, $d\varepsilon_{nn}$, $d\varepsilon_{nt}$	strain increments in the groove coordinates
θ	groove angle between the groove coordinates and the material coordinates
σ_1, σ_2, σ_3	principal stress components
σ_{nn}, σ_{nt}, σ_{tt}	in-plane stress components in the groove coordinates
$\bar{\sigma}_Y$	effective stress obtained from hardening law (MPa)
$\bar{\sigma}_y$	effective stress obtained from yield function (MPa)

different constitutive equations on the required plastic calculation, an analysis on the experimental forming stress limits was performed. The necking phenomenon was simulated by M–K model using a more general code for predicting the forming limits. The selected materials were a bake-hardened steel (BH steel) and an AA6016-T4 aluminum alloy. Several yield criteria such as Von Mises isotropic yield function, quadratic and non-quadratic criterion of Hill's 1948 [8] and the advanced Barlat Yld96 yield function were used to show the influence of the constitutive law incorporated in the analysis on the stress-based forming limits. The effect of the hardening model on the FLSD was analyzed by using two hardening laws, namely Swift law and Voce law. The influence of work hardening coefficient, strain rate sensitivity and the balanced biaxial yield stress on the theoretical FLSD was also presented. The effect of strain path changes on the stress-based forming limits was analyzed. Some relevant remarks about stress-based forming limit criterion concept were presented.

The effects of strain path on the FLCs were examined by applying various bilinear strain paths (non-proportional loading histories). The FLCs are strain path dependent and strain path has an influence on the FLC and therefore is not valid for formability evaluation of sheet metal forming processes undergoing non-proportional loading paths (e.g., see [5,6]). To obtain a criterion with less strain path-dependency, a stress-based FLC or forming limit stress curve (FLSC) was presented and implemented to detect necking [9]. The prediction of the sheet metal strain and stress limits generally presumes plane stress states. This hypothesis is only valid for processes with negligible out of plane stresses such as an open die stamping. Thus, a few works [10,11] have studied the influence of through-thickness compressive normal stress on the prediction of the FLC. It is reported that the sheet metal limit strains increase when the through-thickness compressive normal stress increases.

Recently, Simha et al. [12] presented an extended stress-based FLC that could be used to predict the onset of necking in sheet metal loaded under non-proportional load paths, as well as under three-dimensional stress states. They transformed the conventional strain-based FLC into the stress-based FLC advanced by Stoughton [7]. Then, they converted the obtained curve into the extended stress-based FLC, which was characterized by the two invariants, mean stress and equivalent stress. Assuming that the stress states at the onset of necking under plane stress loading were equivalent to those under three-dimensional loading, the extended stress-based FLC was used in conjunction with finite element computations to predict the onset of necking during tubular hydroforming. Hydroforming of straight and pre-bent tubes of EN-AW 5018 aluminum alloy and DP 600 steel were considered. Experiments carried out with these geometries and alloys were described and modeled using finite element computations. These computations, in conjunction with the extended stress-based FLC, allowed quantitative predictions of necking pressures; and these predictions were found to agree to within 10% of the experimentally obtained necking pressures. The computations also provided a prediction of final failure location with remarkable accuracy. In some cases, the predictions using the extended stress-based FLC showed some discrepancies when compared with the experimental results, and the paper addressed potential causes for these discrepancies.

However, in reference [12], Simha and his co-workers did not examine the strain path independency of their new curve. They also assumed that the formability curve in stress space was not affected by a compressive σ_3, where σ_3 acted in the through-thickness direction. This assumption is not adopted in the current study.

Since necking in some processes such as hydroforming can occur at locations where in addition to the in-plane stresses a through thickness compressive normal stress acts, the plane stress assumption is not proper for these processes. Thus, in this work, the effect of normal stress is considered on the prediction of the extended FLC.

In this paper, the modified M–K theory for the computation of the extended stress-based FLC is developed. Two types of pre-straining on the sheet metal have been loaded to reexamine the effect of strain path on the predicted extended stress-based FLC. The effect of a through-thickness compressive normal stress on the extended stress-based FLC is also investigated theoretically. The verifications of the computed results are done by using some available published experimental data.

2. Theoretical analysis

2.1. Review of the M–K method

In this work, the M–K analysis (e.g., see [13,14]) is represented to compute sheet metal strain and stress forming limits considering the effects of a thorough-thickness normal stress and strain path. The basic assumption of this theory is considering a narrow groove in the sheet metal surface (e.g., a geometrical inhomogeneity). It is assumed that there is a defect region and material thickness of this region is slightly smaller than a safe zone. The zone with a nominal thickness (safe zone) is denoted by "a" and the defect zone is denoted by "b". This geometrical inhomogeneity leads to the plastic instability (localized necking) in the sheet. The schematic representation of the M–K theory is illustrated in Fig. 1. To model the defect zone, a fractional ratio is defined ($f = t_b/t_a$), where "t_a" denotes the thickness of the zone with the nominal