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A methodology for prediction of forming limit stress diagrams considering the strain path effect

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ABSTRACT

The purpose of this study is to present a methodology for prediction of the forming limit stress diagram (FLSD) and reexamine the effect of strain path on prediction of FLSD. The methodology is based on the Marciniak and Kuczynski 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 conditions for non-proportional loading have been achieved by imposing two types of pre-straining on the sheet metal. The effects of grain size, surface roughness and sheet thickness on the FLSD have also been presented. The evaluation of the theoretical results has been performed by using the published experimental data for ST12 low carbon steel alloy.

1. Introduction

The forming limit diagram is used in sheet metal forming analysis to predict how close the sheet metal is to necking. The strain path dependent nature of the forming limit diagram (FLD) causes the method to become ineffective in the analysis of complex sheet metal forming processes. In the literature, the experimental and theoretical results showed that the forming limit stress diagram (FLSD) is less sensitive to the strain path effect than the FLD.

Arrieux et al. [1] proposed a forming limit stress diagram concept, which seems to be independent of the strain path changes. Its utility was promoted as solution to the analysis of multi-stage forming processes.

Zhao et al. [2] showed that FLSDs are not sensitive to the type of strain path.

Stoughton [3] presented the forming limit for both proportional and non-proportional loadings. He developed a FLSD and validated his approach by using data from several non-proportional loadings paths for both aluminum and steel alloys. This approach significantly improved the gauging of forming severity. Also, the new forming limit stress diagram was as easy to be used as the forming limit diagram in the validation of die designs by finite element method.

Ziminiak [4] presented the implementation of the forming limit stress diagrams determined by perturbation theory in FEM simulations. The computed strain distribution has been compared directly with the theoretical forming limit diagrams and forming limit stress diagrams. Applications of FLSD have been presented for sheet metal forming processes such as an L–shape sheet forming, the deep drawing of a square and axisymmetric cups. It has been found that the modification of perturbation theory by a new stress–strain relationship and six components Barlat yield criterion gives good prediction of the onset of necking. The performed experimental verification of this theory has been shown that the agreement between theory and experiment was good.

Safikhani et al. [5] developed a methodology for prediction of the forming limits both in strain and stress forms. All simulations are based on strain gradient theory of plasticity in conjunction with the Marciniak and Kuczynski approach. This approach introduces an internal length scale into conventional constitutive equations and takes into account the effects of deformation inhomogeneity and material softening. The nonlinear second order ordinary differential equation of the thickness of sheet metal has been solved by collocation method. It is shown that this method overcomes the imperfection sensitivity encountered in the conventional Marciniak and Kuczynski method. The evaluation of the theoretical results is performed. The comparison between the experimental and theoretical results for FLDs and FLSDs as

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Notation

a	material constant
d_0	initial grain size
E	Young's elastic modulus
f	imperfection factor
F_{nn}, F_{nt}	force equations in the groove directions
F, F_i	functions vector and its component, respectively
J	Jacobian matrix
k	material constant
$K, n, m, \bar{\varepsilon}_0$	material constants
r	average anisotropic parameter
r_0, r_{45}, r_{90}	ratios of transverse to through-thickness strains under uniaxial tension at 0°, 45° and 90° to the rolling direction
R	initial surface roughness
t	sheet thickness
T	rotation matrix
x, x_j	variables vector and its component, respectively
δx	Newton step
σ_1, σ_2	stress components in the material coordinates
σ_{xx}, σ_{yy}, σ_{xy}	planer components of stress tensor in the orthotropic referential frame
σ_{nn}, σ_{nt}, σ_{tt}	stress components in the groove coordinates in the state of plane stress
$\bar{\sigma}_Y$	effective stress obtained from hardening law
$\bar{\sigma}_y$	effective stress obtained from yield function
$\xi(\alpha)$	ratio of effective stress to major stress
$\dot{\bar{\varepsilon}}$	rate of effective plastic strain
$\bar{\varepsilon}$	effective plastic strain
ε_{1s}^a	pre-strain value
$d\bar{\varepsilon}$	effective plastic strain increment
$d\varepsilon_1$, $d\varepsilon_2$, $d\varepsilon_3$	strain increments in the material coordinates
$d\varepsilon_{tt}$, $d\varepsilon_{nn}$, $d\varepsilon_n$	strain increments in the groove coordinates
$d\varepsilon$	strain increments tensor
λ	Newton step length
ν	Poission's ratio
α	ratio of stresses along the strain path
ρ	ratio of strain increments along the strain path
θ	groove angle between the groove coordinates and the material coordinates

predicted by different methods indicates that the present approach is suitable for these problems.

Haddad et al. [6] used two behavior laws for determination of the forming limit stress curves of orthotropic steel sheet metals and compared them with each other. The first was the classical quadratic Hill's criterion and the second was the 3G theory proposed by CRM of Liege, which assumed that the straining mechanism was described by sliding in the three planes showing maximum shear stresses, i.e. the planes at 45° from the principal stress directions in the isotropic case. Both of the theories enable to determine the forming limit stress states by means of a step-by-step plastic calculation along the strain paths determined in an experimental way on laboratory-drawn parts. For the two cases it has been shown that the forming limit stress curves are independent of the strain path.

Wu et al. [7] presented a detailed study to examine the path dependency of FLSDs based on different non-proportional loading histories which were combinations of two linear strain paths. All simulations were based on crystal plasticity theory in conjunction with the M–K approach. It has been shown that the FLSD is much less path dependent than the FLD. And it has been suggested that the FLSD is more favorite than the FLD in representing forming limits in the numerical simulation of sheet metal forming processes.

Matin et al. [8] presented a method to construct the aluminum alloys sheet metal forming limits corresponding to local necking. Through the manipulation of data collected from only one uniaxial tension test, a method for the calculation of a stress space aluminum sheet metal forming limit is offered. Preserving a reasonable level of simplicity, this method features the advantage of not relying upon assumptions about the material properties of the work piece. Such an advantage is realized by measuring the test specimen at the local neck region. Through finite element analysis, the proposed model is shown to be more accommodating to stamping cases where the effective strains exceed the diffuse necking limit. Because the proposed method is designed to circumvent the traditional difficulties associated with the detection and measurement of strains corresponding to local neck regions of aluminum alloys, it is offered as a tool for the formability analyst who desires to employ a reliable stress space forming limit model in their formability analysis. Although the introduction of the proposed method is motivated by the difficulties associated with determining the limiting strains in aluminum sheet metal, it is fully applicable to steel and other material types.

Stoughton et al. [9] reviewed several theoretical models of sheet metal forming instability, including bifurcation analysis of diffuse and through-thickness neck formation, the M–K model and microscopic void damage models. The equations governing the deformation at the instant of the bifurcation has been shown to be independent of path in all of these models, providing a solid theoretical base for the forming limit stress diagram approach.

Butuc et al. [10] developed a detailed study on the stress-based forming limit criterion (FLSD) during linear and complex strain paths. They analyzed the experimental forming limit stress diagram by applying several combinations of different constitutive equations on the required plastic calculation. They used a more general code for predicting the forming limits which was based on Marciniak–Kuczynski model. They also showed the effect of the yield function and the hardening model on the FLSD by using several yield functions and two hardening laws. The effects of work hardening coefficient, strain rate sensitivity and the balanced biaxial yield stress on the prediction of FLSDs have also been studied.

Uthaisangsuk et al. [11] developed a better approach to predict forming limits which were independent of the deformation history. This approach was based on the forming limit stress diagram. It also takes into account the strain hardening and anisotropy behavior of the material. To determine forming limit stresses, the Nakazima-strip-test has been simulated using FEM. At the point in time when the strains from the crack–critical elements in the simulation reached the forming limit curve (FLD criterion), the maximum stresses on these elements were evaluated. This procedure has been validated with a two-step forming test and a hole expansion test (HET). Both experiments offered forming processes with changing deformation paths in negative and positive range of the strain diagram. The numerical simulations of the HET and two-step forming test were carried out in order to evaluate the applicability of the FLD and FLSD. The results showed that the stress-based criterion (FLSD) characterizes the formability better than the strain-based failure criterion (FLD).

However, the FLD and FLSD are two mathematically equivalent representations of sheet metal forming limits in strain and stress