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Theoretical FLD prediction based on M-K model using Gurson's plastic potential function for steel sheets

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Abstract

The aim of this study is to develop a new analytical method for predicting localized necking in the plastic deformation of sheet metals with internal cavitation. This method is based on the model of Marciniak and Kuczynski (M-K) as well as Gurson's plastic potential function. Stowell's model was used to illustrate void growth behavior during plastic deformation. In order to examine the effect of the voids on localized necking, the void volume fraction was considered in the imperfection factor and the plastic volume constancy principle. The nonlinear system of equations was solved with the modified Newton-Raphson method with globally convergence procedure, using MATLAB software. This new analytical method (M-K-Gurson) was used to predict the forming limit diagram (FLD) of different steel alloy sheets and the results were compared with those of other researchers. The results showed that the M-KGurson method predicted the FLD with good agreement.

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Keywords: M-K model; Gurson's plastic potential; Forming limit diagram; Void volume fraction; Steel alloy sheets

1. Introduction

The experimental determination of the FLD is usually a very time consuming and costly process, and requires special equipment. Therefore, many theoretical models have been developed for the FLD determination [1]. In this regard, the model of Marciniak and Kuczynski (M-K) is one of the most widely used analytical models. This model is based on the existence of an initial geometrical imperfection in the form of a groove in the sheet metal for

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predicting localized necking [2]. In general, the literatures showed that the predicted FLD by M-K model were significantly under the influence of yield criterion and material hardening model. On the other hand, it was observed that in ductile metals, due to hard second phase particles and impurities, internal cavitation occurred during plastic deformation. The existence of voids and their growth during plastic deformation can cause a decrease in the imperfection factor and also accelerate the localized necking. Therefore, the formability of ductile sheet metals can be restricted by the combination and interaction of localized necking and void growth.

Zhixiao et al. [3] proposed a anisotropic damage-instability model for the numerical computation of cavity damage and failure during the superplastic deformation of sheet metals. The model is based on Gurson's constitutive relationship for porous ductile materials and Hill's normal anisotropic and planar isotropy yield criterion. Huang et al. [4] utilized the M-K approach in order to predict the plastic localization by the assumption of a void volume fraction in the geometrical imperfection groove. They used the macroscopic yield criterion of Liao for porous sheet metals based on Hill's quadratic anisotropic yield criterion. Zadpoor et al. [5] combined the porous metal plasticity and the M-K model to predict the formability of high strength aluminum sheets. They found that the combined model accurately predict the fracture limits in the high stress triaxialities.

In this paper, a new analytical method was developed in order to predict localized necking in the plastic deformation of sheet metals with internal cavitation. For this purpose, Gurson's plastic potential function was applied to the M-K model which considers hydrostatic stress and void volume fraction on the yielding function. Stowell's model was used for the description of void growth behavior during plastic deformation, and its effect was considered in the imperfection factor and plastic volume constancy principle. MATLAB software was used to solve the nonlinear system of equations by Newton-Raphson modified method with globally convergence procedure. The FLD of different steel alloy sheets was predicted by this new analytical method and compared with the published results.

2. Theoretical Modelling

2.1. Gurson's plastic potential function

The Gurson's plastic potential function for deformable porous material is expressed as follows [6]:

$$\Omega = \left(\frac{\bar{\sigma}_e}{\bar{\sigma}_y}\right)^2 + 3(f_V)\cosh\left(\frac{3}{2}\frac{\sigma_h}{\bar{\sigma}_y}\right) - (1 + 2.25(f_V)^2) = 0 \tag{1}$$

Where f_V is the void volume fraction, $\bar{\sigma}_e$ is the effective stress from yield criterion, $\bar{\sigma}_y$ is the flow stress from material strain-hardening model and σ_h is the hydrostatic stress. Hosford presented a nonquadratic yield criterion for textured fcc and bcc metals under plane-stress condition as [7]:

$$\bar{\sigma}_e = \frac{1}{[r_{90}(1+r_o)]^{1/a}}(r_{90}|\sigma_1|^a + r_o|\sigma_2|^a + r_o r_{90}|\sigma_1 - \sigma_2|^a)^{1/a} \tag{2}$$

For steel alloys, the exponent a=6 showed good correspondence with experimental results [7,8]. r_0 and r_{90} are the plastic strain ratios at angles 0^o and 90^o with respect to the sheet rolling direction respectively. Since $\sigma_3 = 0$ and assuming $\sigma_2 = \alpha\sigma_1$ and $\bar{\sigma}_e = \phi\sigma_1$, the Hosford's effective stress becomes:

$$\phi = \left[\frac{r_{90} + r_0\alpha^a + r_0 r_{90}(1-\alpha)^a}{r_{90}(1+r_0)}\right]^{1/a} \tag{3}$$

The hydrostatic stress equation under plane-stress conditions becomes: