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Influence of thickness size in sheet metal forming

J.D. Bressan

Department of Mechanical Engineering - Centre for Technological Sciences - Santa Catarina State University - Campus Universitário - 89223-100 Joinville, Brazil.
URL: www.joinville.udesc.br e-mail: dem2jdb@joinville.udesc.br

ABSTRACT: A new approach on the influence of sheet thickness and material plastic properties on the limit strains in thin sheet metal forming is developed, using the strain gradient model that predict the local necking onset from initial thickness imperfections. As a result of the analysis, the definition of a roughness concept parameter is presented: the initial roughness profile inclination to thickness ratio parameter. Also, the critical normalized strain gradient at the onset of local necking can be calculated from the initial assumed roughness profile. A brief review of stretch forming of sheet metal, the diagrams and the limiting strain curves for local necking, FLC, and the limit strain theories are presented. The main characteristics of the sheet metal forming processes are also identified and are based in the press shop practice. The limit strains for different thickness sizes are obtained using the present model and a numerical code developed by the author. Present theoretical model produced reasonable predictions about the influence of thickness size on the FLC.

Key words: Stamping, Deep drawing, Forming Limit Curve, Defects, Thickness.

1 INTRODUCTION

The technologies of sheet metal forming as stamping, deep drawing, stretching and incremental forming are relevant and complex production processes in the automotive, aeronautic and kitchen device industries. The main metals utilized in these industries are steel, aluminium and titanium alloys. Formability of sheet metals is the important and complex issue related to the optimization and quality control of the final product.
Historically, formability has been assessed by simple testing as the Erichsen test. However, formability of sheet metals is a complex attribute that involves different variables as the process parameters and the material properties. In addition, sheet metals defects or inhomogeneities as thickness variations, porosity, roughness and variations in the plastic properties influence the limiting strains of sheet metal forming. Later, the concept of Forming Limit Curves - FLC has been developed to assess sheet metal formability [1]. The Forming Limit Diagram - FLD displays the principal in-plane true strains, ε_1 and ε_2 , attained by the sheet metal at critical points during testing methods or production process, i.e. the FLC. Two types of curves can be plotted: local necking or fractures strains.
Experimental and theoretical predictions of the local necking and fracture strains have been investigated by academic researchers and industry professionals. Various mathematical models have been proposed to predict the limiting curves of sheet metals for deep drawing, stretching and constant or variable strain path processes [2,3,4,5,6]. These theoretical models considered the material plastic properties and thickness imperfections only to predict the limiting strains, but do not taking into account the nominal value of thickness size.

2 LOCAL NECKING MODELLING

The stretch forming or deep drawing of sheet metal are considered failed when terminated by fracture or local necking. Within the biaxial stretching region of the FLD, experimental investigations have shown that rupture is generally preceded by local necking or by shear process [5]. The process of strain localization in sheet metal forming have been investigated by the author [6], using the concept of strain gradient development. The mathematical model assumes that the process of neck initiation and growth is a continuous process of strain localization due to initial variations in thickness of the sheet metal. This initial variation in thickness is characterized by the parameter μ which is the initial normalized gradient in the transversal area or defect.

The local necking or limit strain occurs when the strain gradient λ attains a critical value $\lambda_{crit} = 20$.
In the present approach, the influence of thickness size h_o on the limit strain is analysed through the initial parameter μ and the adopted initial roughness profile as seen in Fig.1. Thus, in the initial element of sheet metal, the local imperfections in thickness $h_o(x)$ can be related to the roughness profile by,

$$\mu = \frac{1}{A_o}\frac{dA_o}{dx} = \frac{1}{h_o}\frac{dh_o}{dx} = \frac{1}{h_o}\,\mathrm{tg}\,\theta \qquad (1)$$

where A_o = initial transversal area, $h_o = h_o(x)$ = initial thickness size, tg θ = roughness profile inclination, x = coordinate axis perpendicular to the local neck.

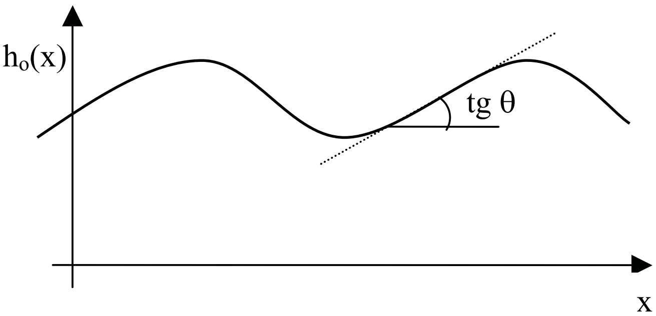

Fig.1 Initial thickness profile and roughness model of sheet metal related to equation (1).

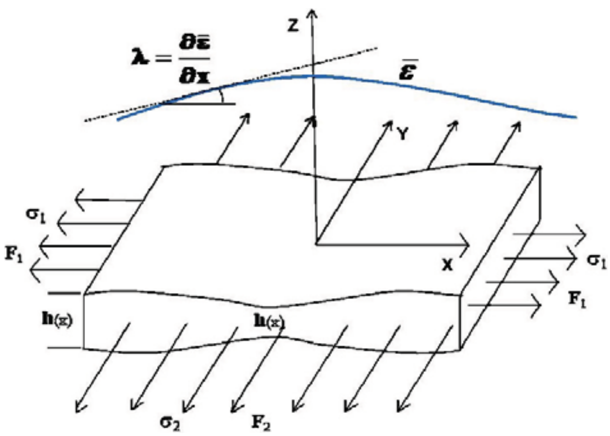

Fig.2 Element of sheet metal under biaxial stretching, showing a local neck and the definition of the strain gradient λ.

Present approach analyses a thin sheet metal with strain hardening and strain rate hardening behavior which constitutive equation for flow stress is,

$$\bar{\sigma} = k\left(\varepsilon_o + \bar{\varepsilon}\right)^n \dot{\bar{\varepsilon}}^M \qquad (2)$$

where k = strength coefficient, $\bar{\varepsilon}$ = equivalent true strain, ε_o =prestrain, n = strain hardening coefficient, $\dot{\bar{\varepsilon}}$ = equivalent strain rate, M =strain rate sensitivity coefficient.
Also, the anisotropic yield criterion proposed by Hill [7] which accommodate R-value less than 1, is used,

$$\bar{\sigma}^m = \frac{1}{2(1+R)}\left[(1+2R)\left|\sigma_1 - \sigma_2\right|^m + \left|\sigma_1 + \sigma_2\right|^m\right] \qquad (3)$$

where R = normal anisotropy, m = parameter of anisotropy (m = 1.14+0.86R) [5], σ_1 and σ_2 are the sheet in-plane principal stresses, see Fig.2.
The governing equation for the local necking formation and growth [6] from the initial thickness imperfection μ in sheet metal forming processes is,

$$\frac{\partial\lambda}{\partial\bar{\varepsilon}} = \frac{\mu}{M} + \frac{1}{M}\left\{\frac{\alpha}{(1+\alpha)z} - \frac{n}{(\varepsilon_o + \bar{\varepsilon})}\right\}\lambda \qquad (4)$$

where $\lambda = \partial\bar{\varepsilon}/\partial x$ = strain gradient in the local neck, $\alpha = \partial\varepsilon_1/\partial\varepsilon_2$ = strain path and z = subtangent which is defined as,

$$z = \frac{[2(1+R)]^{1/m}}{2(1+\alpha)}\left\{\frac{\left|\alpha-1\right|^{m/(m-1)}}{(1+2R)^{1/(m-1)}} + \left|\alpha+1\right|^{m/(m-1)}\right\}^{\frac{m-1}{m}} \qquad (5)$$

Equation (4) can be solved analytically or numerically to describe the development of local strain gradient during sheet metal forming processes. Varying the strain path α, the limiting strain curve or FLC can be calculated when the strain gradient λ attains a critical value $\lambda_{crit} = 20$ or when $\lambda/\mu = (\lambda/\mu)^*$ = constant. Introducing equation (1) in $(\lambda/\mu)^*$,

$$(\lambda/\mu)^* = \frac{h_o}{\mathrm{tg}\,\theta}\lambda_{crit} \qquad (6)$$

3 RESULTS AND DISCUSSIONS

The roughness inclination parameter tg θ can be evaluated from roughness measurements for short wave or long wave profiles. From experimental results, this parameter is less than tg $10^o = 0.176$, thus, the critical normalized strain gradient is,

$$(\lambda/\mu)^* \cong 113.4\,h_o \qquad (7)$$

Therefore, the critical normalized strain gradient at the instant of local necking inception $(\lambda/\mu)^*$ increases linearly with the sheet thickness h_o , consequently, the FLC curve also moves upwards in the FLD. Thicker sheet metal must generate higher limit strains than thinner ones, but the correlation of limit strains with the sheet thickness is not linear.

For a material exhibiting M = 0 and ε_o = 0, the critical normalized strain gradient at the instant of local necking is,

$$(\lambda/\mu)^* = \frac{(1+\alpha)z/\alpha}{\frac{n}{\varepsilon_1^*}-1} \tag{8}$$

where ε_1^* is the limit strain in the principal direction 1. Introducing equation (7) into equation (8), the limit true strain ε_1^* or the FLC curve can be evaluated as,

$$\varepsilon_1^* = \frac{n}{1+\frac{(1+\alpha)z/\alpha}{113.4\,h_o}} \approx n \tag{9}$$

Thus, the thickness size h_o has neglecting effect on the limit strains for strain rate insensitive materials, but the n-value may vary slightly with thickness. Alternatively, for material strain rate sensitive or exhibiting M-value, the thickness size h_o has an important role on the limit strains or the FLC curve. The theoretical effect of h_o on the limit true strain curve for steel sheets of 0.5 , 1.0 , 1.5 , 2.0 , 2.5 and 3.0 mm can be evaluated in Fig.3. The FLC is plotted in the positive region or the biaxial stretching region of the FLD. The steel is assumed isotropic, R = 1 and m = 2, and to have the equivalent flow stress of $\bar{\sigma}=k\left(0.05+\bar{\varepsilon}\right)^{0.22}\dot{\bar{\varepsilon}}^{0.012}$ MPa , i.e, n = 0.22 and M = 0.012.
According to equation (1), the initial thickness imperfection parameter μ decrease from 0.352 to 0.059 as the thickness size h_o increases from 0.5 mm to 3.0 mm, hence, the limiting true strains increases about 20%. Therefore, thinner sheet metal will have lower limit strain or FLC, i.e., lower resistance to local necking. However, thicker sheet metal tends to a maximum theoretical limit of true strain or major true strain of about 0.34 for this adopted material exhibiting work hardening coefficient n = 0.22 and strain rate sensitivity coefficient M = 0.012. Although M-value is very small, it is sufficient to delay the onset of local necking, increasing the major true strain ε_1^* from 0.22 to 0.31 for a steel sheet of thickness of 1 mm.

4 CONCLUSIONS

From the prediction of limit strains curves in the biaxial stretching region of FLC for thin steel sheets with thickness h_o varying from 0.5 mm to 3.0 mm,

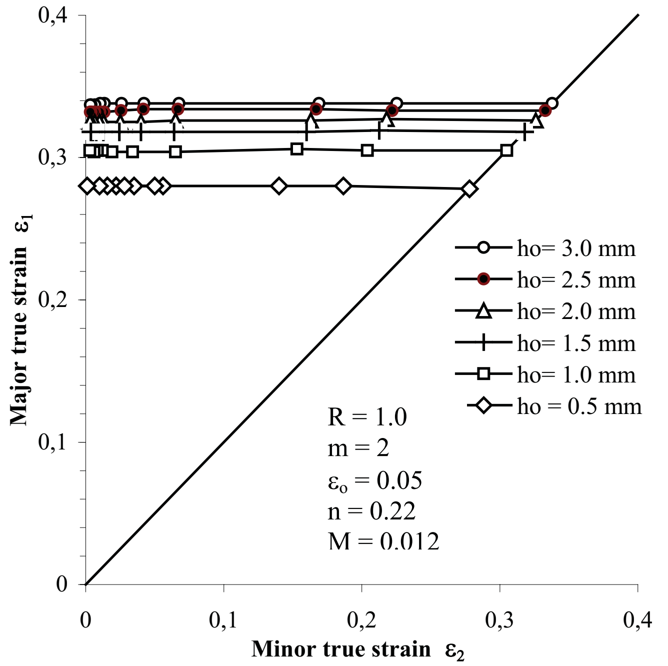

Fig.2 Prediction of the influence of thickness size h_o on the limit strains or FLC for isotropic steel sheet with flow stress $\bar{\sigma}=k\left(0.05+\bar{\varepsilon}\right)^{0.22}\dot{\bar{\varepsilon}}^{0.012}$, according to present model.

the following conclusions can be drawn:
- present theoretical model of strain gradient development produced reasonable predictions about the influence of thickness size on the FLC,
- the critical normalized strain gradient at the onset of local necking can be assumed $(\lambda/\mu)^* \cong 113.4\,h_o$
- thicker steel sheets have higher limit strains of up to 20%, thus, have higher resistance to local necking
- steel sheets exhibiting the equivalent flow stress of $\bar{\sigma}=k\left(0.05+\bar{\varepsilon}\right)^{0.22}\dot{\bar{\varepsilon}}^{0.012}$ have a maximum major true strain of 0.34 in the stretching region of the FLD.

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