Journal of Manufacturing Processes 21 (2016) 134–140

Contents lists available at ScienceDirect

Journal of Manufacturing Processes

journal homepage: www.elsevier.com/locate/manpro

Review

The effect of the through-thickness normal stress on sheet formability

Bolin Ma [a], Keshan Diao [b], Xiangdong Wu [a,*], Xinjun Li [a], Min Wan [a], Zhengyang Cai [a]

[a] School of Mechanical Engineering and Automation, Beijing University of Aeronautics and Astronautics, Beijing 100191, PR China
[b] State Key Laboratory of Development and Application Technology of Automotive Steels (Baosteel Group), Shanghai Baoshan 201900, PR China

ARTICLE INFO

Article history:
Received 13 May 2015
Received in revised form
13 November 2015
Accepted 23 December 2015

Keywords:
Sheet metal
Forming limit curve
3D-stress states
M-K model
Through-thickness normal stress

ABSTRACT

Sheet formability is limited by the onset of localized necking or fracture, and the limit strain is important to measuring sheet formability. The forming limit curve (FLC), which maps the limit strain under different strain paths into the strain space, provides a convenient and useful way to predict material failure in the sheet forming process. The FLC is closely related to many factors, such as the material mechanical properties, stress state, temperature and forming speed. This paper focuses on the influence of the through-thickness normal stress on the FLC, in which a modified M-K model with a corresponding algorithm under the 3D-stress state is proposed. The through-thickness normal stress is obtained by analyzing the Nakazima test and simplifying it. Both experimental and reference data are applied to the model validation, which indicates a higher prediction accuracy when the sheet thickness is introduced into the model. Theoretical FLCs under different ratios of t_0/D show a linear relationship between the sheet thickness and the limit strain increment in tension–tension states.

Contents

1. Introduction

The experimental forming limit diagram in strain space (FLD_ε) was proposed by Keeler [1] and Goodwin [2] as a failure criterion in the sheet forming process to measure the sheet formability. The forming limit curve (FLC) is a line that passes through the major and minor strain pair for each strain path representing necking or fracture. Experimental and theoretical investigations on FLC were carried out comprehensively. Two main laboratory approaches, the so-called out-of-plane stretching (e.g., the Nakazima [3] test and the Hecker [4] test) and in-plane stretching (e.g., the Marciniak [5] test), were generated to determine the FLCs. It is more convenient to use the out-of-plane method than the in-plane method in the experimental determination of the FLC [6], and the Nakazima method has been widely used. In the determination process of theoretical FLCs, the results are usually related to the yield criteria, hardening models and instability criteria [7,8]. Most of the proposed instability criteria are based on the assumption of plane-stress (2D-stress) states, such as Hill's localized instability theory [9], Swift's diffuse instability theory [10] and the M-K theory [11].

The FLC in strain space is susceptible to the strain path [12], stress state [13], and other factors [14]. This influence would be weakened if it is mapped into stress space [15,16]. Zhang et al. [17,18] have performed works introducing the Hill 1948 and Barlat

* Corresponding author. Tel.: +86 13426078055.
E-mail address: wuxiangdongbuaa@163.com (X. Wu).

http://dx.doi.org/10.1016/j.jmapro.2015.12.006

1989 yield criteria into the M-K model to demonstrate that the normal stress improves the sheet formability both in strain space and stress space. The M-K method was also used by Hashemi et al. [19] to verify the effect of the through-thickness normal stress on the extended stress-based FLC. There is no doubt that the FLC in strain space is more convenient than that in stress space for the stamping process, so more investigations have focused on the FLC in strain space. The works of Nurcheshmeh et al. [13] have shown that the influence of the through-thickness stress on the FLC obtained through applying the M-K model under the three-dimensional stress state decreases as the magnitude of the pre-strain increases. The work of Assempour et al. [20], who focused on extending the M-K model by using an energy equation and a three-dimensional form of the yield function in the groove zone, indicated that the compressive normal stress shifts the FLC up. However, it should be noted that the works mentioned above were based on assuming a constant normal stress on the sheet surface, while the relationships between the normal stress and the other stress components was ignored. An further development was conducted by Smith et al. [21,22], in which a hypothetical linear relation between the normal stress and the first stress component was proposed based on analyzing the stress state in the hydro-bulge process. With Gotoh's model, not only the ratio of the normal stress to the first stress component but also the ratio of the strain components in-plane could affect the theoretical FLC. From the substantial existing works, it is apparent that the influence of the through-thickness normal stress on the FLC cannot be ignored.

The through-thickness normal stress also impacts on the sheet formability in a specific forming process. Abdel-Rahman [23] has reported that a particular level of applied normal stress enhances the sheet formability and prevents fracture in the deformation process. In the sheet stretch-bend deformation process, the stress along the normal direction has been confirmed as one of the factors affecting the sheet formability, and the influence on the sheet formability depends on the t/R ratio [24,25]. In the sheet hydro-mechanical deep drawing process, the through-thickness stress was taken into account for a higher precision by Liu et al. [26]. Lu et al. [27] introduced the normal stress into a shell element for providing a better solution for springback. As seen from these works, the through-thickness stress has an obvious impact on the sheet formability, most significantly in the forming process and even in the tube hydroforming process [28,29].

In-plane tests carried out by Kleemola et al. [30] show that the limit strain does not depend on the sheet thickness, but out-of-plane test results indicate that the FLC determined by the Nakazima test increases with the sheet thickness increasing [31–33]. The contact between the sheet inner surface and punch can be used to explain this phenomenon, which would inevitably lead to a larger through-thickness normal stress in an out-of-plane test than in an in-plane test [34]. This stress causes out-of-plane FLCs to be greater than in-plane FLCs [35], indicating that the larger sheet thickness causes a more intense through-thickness normal stress [31]. Consequently, it is significant for a researcher to find the relationship between the normal stress and sheet thickness in the Nakazima test and clarify the influence of the through-thickness normal stress on the FLC.

It is apparent that substantial progress has been made toward obtaining a better understanding of the influence of the through-thickness normal stress on the sheet formability. However, the relationship between the normal stress and the other stress components is replaced by a constant value in many works. This paper develops the relationship between the three principal stress components by analyzing the Nakazima test process to predict the theoretical FLCs of different sheet thicknesses using a modified M-K model. The paper demonstrates that by citing published data of IF steel and experiments with a Qste600TM, the modified model has a higher prediction accuracy on the right-hand side of the FLC. The paper also theoretically demonstrates a linear relationship between the sheet thickness and the limit strain when it is under the tension–tension strain condition.

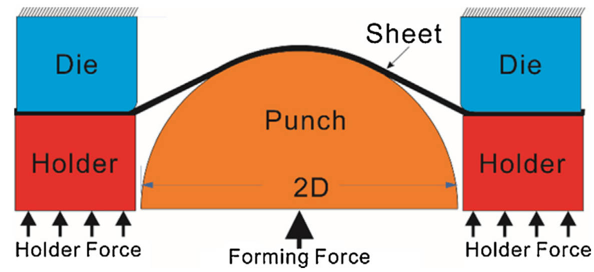

Fig. 1. Nakazima test process [36].

2. Expansion process

In the Nakazima test process, a specimen marked with grids is fixed on the concave tool by the holder and stretched by a rigid hemispherical punch until failure occurs on the sheet. The following work is to measure the grid strain near the failure region and map the obtained strain components in the $\varepsilon_1 - \varepsilon_2$ coordinate system. The above works are repeated with different width specimens. Afterwards, the strain limit points of the different specimens are connected into a line, and the FLC of this material is obtained. The Nakazima test is shown in Fig. 1 [36].

The stress states at position (D, θ, φ) in the Nakazima test are presented in Fig. 2, where the friction is ignored to simplify the model. The stress components along the r, θ and φ directions are denoted by σ_r, σ_θ and σ_φ, respectively. It is obvious that the three principal stress components could be presented as follows:

$$\sigma_1 \equiv \sigma_\theta \sigma_2 \equiv \sigma_\varphi \sigma_3 \equiv -\sigma_r$$

Denoting the area with the corresponding stresses by variables S_i and σ_i ($i = \theta, \varphi, r$), S_i can be defined as follows:

$$\left.\begin{aligned} S_\theta &= D \sin\theta \, t_\theta d\varphi \\ S_\varphi &= D \sin\theta \, d\theta \left(\frac{t_\theta + t_{\theta+d\theta}}{2}\right) \\ S_r &= D^2 \sin\theta \, d\varphi d\theta \end{aligned}\right\} \quad (1)$$

The force equilibrium equation along the r direction is presented as Eq. (2), Combining Eqs. (1) and (2), Eq. (3) is obtained as follows.

$$\sigma_r S_r - \sin\frac{d\theta}{2}\sigma_\theta S_\theta - \sin\frac{d\theta}{2}\sigma_{\theta+d\theta} S_{\theta+d\theta} - 2\sin\frac{d\beta}{2}\sigma_\varphi S_\varphi = 0 \quad (2)$$

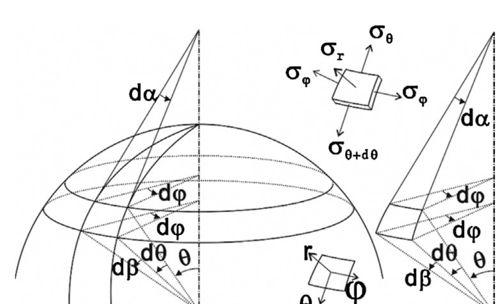

Fig. 2. Stress states in Nakazima test.