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To cite this article: W Q Liu et al 2018 J. Phys.: Conf. Ser. 1063 012110

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Parameter calibration for a shear modified GTN model and its application to forming limit prediction

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Abstract. Damage evolution is an unavoidable problem in the forming process of sheet metal, and an improper forming technology may cause ductile fracture of the final parts. The damage mechanics theory can give great insight to the failure mechanism and the numerical simulation using damage model can provide a new way to predict the fracture behaviour for sheet metal. The shear modified GTN model by Nahshon and Hutchinson with a piecewise interpolation function was applied, which can capture the damage evolution under both low and high stress triaxiality. Then, a method combined numerical simulation and optimization algorithm was adopted to calibrate the damage-related parameters. Furthermore, the shear modified model was used to predict the forming limit of a high strength steel 22MnB5.With the help of digital image correlation technique (DIC), both the strain field and forming limit curve obtained by the numerical simulation were compared with the experimental ones, and satisfactory results are obtained.

1. Introduction

Sheet metal forming is an important technology which is widely used in automobile industry. During the forming process, ductile fracture in sheet metal may happen due to the unreasonable parameters or serious friction. The essential reason of metal fracture is the nucleation, growth and coalescence of voids under large plastic deformation. The above reason can be treated as the evolution of material damage. To predict the damage evolution or the formability of sheet metal, several methods have been proposed.

The porous damage model proposed by Gurson [1] and further modified by Tvergaard and Needleman [2], which is well known as the GTN model, has been widely used to predict the ductile fracture of metal material. The predicted accuracy of GTN model in medium to high stress triaxiality can be guaranteed, but the efficacy in low stress triaxiality is defective. There is no damage evolution in the pure shear stress state if the void nucleation is not invoked. To cover the shortage, some modified versions of GTN model have been introduced and applied successfully in their works [3-5]. In addition to the damage mechanics based method, many macro methods were also proposed. Among them, the forming limit diagram (FLD) is the most widely used criterion to evaluate the formability of

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sheet metal [6]. It consists of limited strain points that cover the stress state from uniaxial tension to equi-biaxial tension. To construct the FLD for various materials, classic test methods have also been developed [7,8].

In this work, the formability of a high strength steel 22MnB5 was studied. To predict the damage evolution of steel 22MnB5 accurately, an extension of the GTN model considering shear damage was employed. The corresponding numerical procedure was integrated into the finite element code Abaqus/Explicit through VUMAT. Then, a series of tensile experiments were performed to calibrate the damage parameters. Finally, both experiment and simulation studies of Nakazima test were carried out.

2. Shear modified damage model

The GTN model, which can predict the evolution of void damage, is expressed as:

$$\Phi = \left(\frac{\sigma^{eq}}{\bar{\sigma}_m}\right)^2 + 2f^* q_1 \cosh\left(\frac{3q_2\sigma^n}{2\bar{\sigma}_m}\right) - \left(1 + q_3 f^{*2}\right) = 0 \tag{1}$$

where, σ^{eq} is macro Von Mises equivalent stress; σ^{h} is macro hydrostatic stress; $\bar{\sigma}_{m}$ is yield stress of the matrix material; q_1, q_2, q_3 are the modified parameters introduced by Tvergaard; f^* is a function of void volume fraction f.

The void evolution expression includes two parts, void growth and nucleation of new voids, as shown in equation (2).

$$df = df_g + df_n \tag{2}$$

Assuming that the matrix material is incompressible, the following equation can be obtained for void growth:

$$df_{\mathfrak{g}} = (1 - f)d\mathbf{\varepsilon}^{\mathfrak{p}} : \mathbf{I}$$
(3)

The strain-controlled nucleation rule is employed in this work and can be expressed as follows:

$$df_n = Ad\overline{\varepsilon}^p \tag{4}$$

$$A = \frac{f_N}{S_N \sqrt{2\pi}} \exp\left[-\frac{1}{2} \left(\frac{\overline{\varepsilon}^p - \varepsilon_N}{S_N}\right)^2\right]$$
(5)

where, f_N is the volume fraction of potential nucleated particles, ε_N is the mean strain for void nucleation, S_{N} is the corresponding standard deviation. \overline{E}^{p} is the equivalent plastic strain of the matrix material and can be updated by the equivalent plastic work principle. For most metal materials, $q_1 = 1.5$, $q_2 = 1.0$, $q_3 = 2.25$, $S_N = 0.1$, $\varepsilon_N = 0.3$ are suitable[9].

K. Nahshon et al. [3] introduced a modification term into the GTN model to concern the shear effect on the damage evolution under low stress triaxiality. It is given as:

$$df_s = k_\omega \omega(\sigma) f \frac{s_{ij} d \varepsilon_{ij}^p}{\sigma^{eq}}$$
(6)

where, df_s is increment of equivalent void volume fraction which represents the effect of void shear, k_{ω} is a shear coefficient that needs further calibration, $\omega(\sigma)$ is a function of stress state.

But the effect of this modification term is rather strong in some certain stress states, where the tress triaxiality is relatively high. To overcome this disadvantage, Nielsen et al. [10] introduced an interpolation function as:

$$\Omega(T) = \begin{cases} 1 & T < T_1 \\ \frac{T_2 - T}{T_2 - T_1} & T_1 \le T \le T_2 \\ 0 & T > T_2 \end{cases}$$
(7)

where, T is stress triaxiality. And then, the shear modification term becomes:

$$df_{s} = k_{\omega}' \Omega(T) \omega(\sigma) f \frac{s_{ij} d\varepsilon_{ij}^{p}}{\sigma^{eq}}$$
(8)

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The numerical implementation method was developed based on the work of Aravas [11]. And the corresponding code was integrated into ABAQUS/Explicit as a user material subroutine VUMAT.

3. Parameter calibration and application to FLD prediction

3.1. Parameter calibration

To calibrate the parameters in shear modified GTN model, a series of tensile experiments were designed. These experiments realized different stress states, including uniaxial tension, pure shear and shear-tension combination. As for uniaxial tension, typical dog-bone shaped sample was adopted, while for other stress states, three samples of specific shape were designed. The sketches of these samples are shown in figure 1.

Sample Number	Stress Triaxiality	Sample geometry
1	T≈0	
2	0 <t<0.33< td=""><td></td></t<0.33<>	
3	Between sample 1 and sample 2	

Figure 1. Samples for parameter calibration.

To calibrate the parameters in the original GTN model, i.e., f_0 initial void volume fraction, f_c critical void volume fraction, f_F final void volume fraction and f_N , a method combined numerical simulation and optimization algorithm was applied [12]. For the shear-related parameters, the value of k_{ω} for sample 1 and 2 was identified firstly which can make the simulated force-displacement curves appropriately compatible with the experimental ones. Then the parameters k_{ω}', T_1, T_2 were calibrated through equation (9) and GA method. All the calibrated parameters are listed in table 1.

$$\int_{0}^{D_{f}} k_{\omega}' \Omega(T_{f}) dD = k_{\omega}^{i} D_{f}$$
⁽⁹⁾

where, T_f is the stress triaxiality of the point where fracture first occurs; D_f is fracture displacement; k_{ω}^i is the shear coefficients for sample 1 and 2.

 Table 1. Damage-related parameters.

Parameter	Value	Parameter	Value
f_0	0.002	k' _w	2.7
$f_{ m N}$	0.0155	T_1	0.1998
$f_{ m C}$	0.05	T_2	0.5769
$f_{ m F}$	0.13	١	١

The simulated results for sample 1 and 2 are compared with the experimental data as shown in figure 2. To further verify the validity of the shear modified GTN model with interpolation function, another simulation and experiment were performed on sample 3. It shows that all the curves resulted

from modified GTN model match the experimental ones very well. The simulated results by the original GTN model are also plotted in figure2, but the difference compared with the experimental curves is obvious.



Figure 2. Comparison between the experimental and simulated force-displacement curves.

3.2. Nakazima experiment and simulation

Nakazima test is a common way to obtain the FLD of sheet metal. In this section, both the Nakazima experiment and simulation were performed on a high strength steel 22MnB5. The Nakazima device contains a hemispherical punch, a blank holder with draw bead which can prevent the sheet sliding during bulging forming, a die with circular groove which matches with the draw bead on the blank holder. To give a study on the deformation history of sheet metal and calculate the limit strain points, the DIC technology by ARAMIS software was integrated. Both the Nakazima device and the finite element model are given in figure 3. The geometric model of sample was meshed by "continuum, 3D stress, 8-node linear brick, reduced integration together with hourglass control" (C3D8R) elements, and to save calculation time and keep precision, the elements in the central region are much finer and the size of 1mm was selected, while the elements in the marginal area are relatively coarse. Because none deformation of the punch and die, these two parts were set as rigid body and meshed by four-node shell element.



Figure 3. Nakazima device and finite element model.

To obtain limit strain points of different strain paths, samples with five different widths were cut, and the preparation technology meets the International Standard ISO 12004-2(2008). Before bulging

forming, random black and white spots were painted on one side of the sample surface. Meanwhile, a silicone pad with a thickness of 1mm was placed between the punch and sample surface without spots, which can reduce the friction and make the fracture position close to the peak of formed sample. Accordingly, the friction coefficient between the sample and punch is small, and a value equal to 0.025 was set in the finite element model. The deformed samples are shown in figure 4.



Figure 4. Samples after bulging forming.

Figure 5 gives a comparison of the equivalent strain field between the calculated results by ARAMIS and the numerical simulation. The width of the selected sample is 80mm and the strain field is chosen at three deformation steps. It shows that the simulation with the shear modified GTN model can predict the fracture location and strain distribution of the deformed sample satisfactorily. According to the International Standard ISO 12004-2(2008), the position-dependent method was adopted to calculate the limit strains. The FLD obtained by Nakazima test and numerical prediction is shown in figure 6 and there are some differences between the results of these two methods. It may be caused by the friction which is not exactly the same. On the other hand, the frequency of taking pictures is also an influential factor which needs to be further analysed.



Figure 5. Comparison between the simulated equivalent strain field and the experimental data



Figure 6. FLD obtained by Nakazima test and simulation.

Conclusion

In this paper, the shear modified GTN model with an interpolation function was employed to study the formability of a high strength steel 22MnB5. The damage-related parameters were calibrated through experiments under different stress states and relevant numerical method. To establish FLD of the tested material, both the Nakazima test and simulation were carried out. The simulation results are satisfactory by comparing experimental data. But, for a more accurate research, several aspects must be further considered, such as anisotropy, strain rate, mesh-dependency problems and so on.

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Acknowledgments

This research was financially supported by National Natural Science Foundation of China (Grant No. 51705065) and Fundamental Research Funds for the Central University (DUT17JC38).