Parameters Determination of GTN Model and Damage Analysis of Aluminum Alloy 6016 Sheet Metal

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Abstract. Taking the material of AA6016 (Aluminum Alloy 6016) which is widely used in automobiles as the object of this study, the mechanical properties based on GTN (Gurson-Tvergaard-Needleman) model had been investigated. The parameters of the GTN model which were used for simulation were identified by uni-axial tensile test, parameter fitting and the inverse finite element method. Then, the simulation of the uni-axial tensile test was done by developing subroutine of UMAT (User-Defined Material) based on LS-DYNA. The results show that the damage and fracture of AA6016 have good agreements with the experiment. Further, the influences of different damage parameters f_0 and f_n on the mechanical properties were investigated, which verifies the rationality of the GTN parameters. It is of interest that in the results of both simulation and experiment, the direction of fracture on the plate tensile specimen is 60 °, instead of the 45 °or 90 °obtained in previous literatures.

Introduction

AA6016 has been successfully used in automobile panels due to its excellent ductility in recent years. However, with the accumulation of the deformation during the process of sheetforming, there is a possibility that cracks and even fractures will occur, which will lead to a lot of waste and reduce the products pass rate. It is hard to avoid and has plagued the actual production for a long time.

The research of mesoscopic damage mechanics[1] has pointed out that for material such as AA6016 which without initial macro-cracks , the damage and fracture appeared during the process of sheet forming is mainly the result of the nucleating, growing and coalescing of micro-voids or micro-cracks. So the choice of a suitable material constitutive model with micro-cracks and micro-voids will contribute to understanding the damage and fracture mechanism of AA6016 in the process of sheet forming.

Since McClintock was first and foremost in establishing the micro-void material constitutive model[2], macro damage mechanics were combined with micro damage mechanics in such a way that it offered researchers a new method to solve the damaging and fracturing phenomenon of material without the initial macro cracks.

Based on the research of McClintock and Rice[4], Gurson[3] developed the well-known Gurson model. He abandoned the hypothesis of infinite body and developed a finite cell model containing micro voids, which laid the foundation for the description of damage(such as taking the void volume fraction as the damage variable), and the plastic theory of macroscopic volume expansion.

In 1979, Tvergaard and Needleman[5,6] modified the Gurson model by introducing parameters q_1 and q_2 and established the void fusion equation f^*, which further corresponds to the evolution process in electron microscopy experiment. The modified Gurson model is called GTN model. Though the GTN model has been widely accepted as a typical model used to study the material'sinner mesoscopic damage, the complication of numerical method and excessive damage parameters make it difficult to describe the evolution process of inner voids.

In this paper, the uni-axial tensile test for AA6016 sheet metal was done, combined in combination with parameter fitting, to obtain parts of the mechanical parameters of the GTN model. Then the simulation of uni-axial tensile was done by developing subroutine of UMAT (User-Defined Material)) based on LS-DYNA, and the left unknown parameters of the GTN model were obtained by using inverse finite element method [16]. Additionally, the influences of $f_0$and $f_n$on evolution process of voids are also discussed.

The GTN Model

Modified GTN model

The plastic potential state equation of GTN model is shown as follows:

$$\varphi=\left(\frac{\sigma_{eq}}{\bar{\sigma}_{mis}}\right)+2q_1 f^* cosh\left(-\frac{3q_2\sigma_H}{2\bar{\sigma}_{mis}}\right)-\left(1-f^{*2}\right). \quad (1)$$

where$\sigma_{eq} = \sqrt{3/2S_{ij}S_{ij}}$is the macroscopic Von-Mises equivalent stress,$-\sigma_H = 1/3\sigma_{kk}$is the macroscopic hydrostatic stress, $S_{ij} = \sigma_{ij} - 1/3\sigma_{kk}\delta_{ij}$ is the deviatoric stress tensor,$\sigma_{ij}$is the flow stress, $\delta_{ij}$is the Kronecker delta, and $\bar{\sigma}_{mis}$ is the equivalent stress of the matrix material;q_1 and q_2 are the correction coefficients introduced by Tvergaard and Needleman, with $q_2 = q_1^2$; f is the void volume fraction, and f^* is the function of f and it is defined as follows:

$$f^* = \begin{cases} f \\ f_c + kk(f - f_c) \end{cases}. \quad (2)$$

wheref_c represents the critical value when the void coalescence occurs, kk is the void growth acceleration factor corresponds to porosity rate after voids grew and is shown as follows:

$$kk = \frac{f_n^* - f_c}{f_f - f_c}. \quad (3)$$

where f_n^* is the maximum admissible void volume fraction when stress bearing capacity equals to zero, and f_f is the critical value corresponds to the complete damage of the material.

From the Eq. 2 it is clearly that as $f \to f_f$ and $f^* \to f_n^*$, the material will lose its bearing capacity gradually. To ensure $\boldsymbol{\sigma}_{ij} = \mathbf{0}$ when it comes to the complete damage of the material, $f_n^* = 1/\mathrm{q}_1$ can then be obtained from Eq. 1 and Eq. 2. And when $f^* = f$ and $f^* = 0$, Eq. 1 degrades into Gurson model and Von-Mises yield function respectively.

In porous materials, the plastic flow potential φ not only relates to void volume fraction f,but also depends on $\bar{\varepsilon}_{mis}^{pl}$, which represents the cumulative plastic strain under material micro state and can be obtained by equivalent plastic power principle as follows:

$$\left(1-f\right)\bar{\sigma}_{mis}d\bar{\varepsilon}_{mis}^{pl} = \boldsymbol{\sigma} : d\boldsymbol{\varepsilon}^{\boldsymbol{p}}. \quad (4)$$

$$d\bar{\varepsilon}_{mis}^{pl} = \frac{\boldsymbol{\sigma} : d\boldsymbol{\varepsilon}^{\boldsymbol{p}}}{\left(1-f\right)\bar{\sigma}_{mis}}. \quad (5)$$

where $d\bar{\varepsilon}_{mis}^{pl}$ is the cumulative equivalent plastic strain increment of the matrix material, and $d\boldsymbol{\varepsilon}^{\boldsymbol{p}}$ represents the macroscopic plastic strain increment.

Void Volume Fraction *f* of Voids Evolution GTN Model

The modified GTN model involved the evolution equation of void volume fraction.It divides the damage evolution into two parts,which describes the growth of existing voids and nucleation of new voids. In this way the void volume fraction *f* will be influenced. The function is characterized by:

$$df = df_{growth} + df_{nuclear tion} . \tag{6}$$

where f_{growth} denotes the growth of voids, while $f_{\mathrm{nuclear tion}}$ describes the contribution of newly nucleated voids.

As the material is incompressible, the existing void volume fraction f_{growth} is related to mean plastic strain and can be written as:

$$df_{growth} = (1 - f)\, d\boldsymbol{\varepsilon}^{p} : \boldsymbol{I} . \tag{7}$$

here, $\boldsymbol{I}$ is the third order unit tensor and $\mathrm{d}\varepsilon^{\mathrm{p}}$ stands for the plastic strain rate.

The nucleation of voids is described by:

$$df_{nuclear tion} = A_N d\bar{\varepsilon}_{mis}^{pl} . \tag{8}$$

The void nucleation constant is shown as follow:

$$A_N = \frac{f_n}{s_N \sqrt{2\pi}} exp\left\{ -\frac{1}{2}\left(\frac{\bar{\varepsilon}_{mis}^{pl} - \varepsilon_N}{s_N} \right)^2 \right\} . \tag{9}$$

here, A_N is the constant represent the void nucleation, and f_n is the volume fraction of void nucleating particles. A_N/f_n follows the normal distribution, in which $\varepsilon_N$and $\mathrm{s_N}$are the mean strain (expectation in mathematics) and the corresponding standard deviation respectivelyboth for void nucleation. In conjunction with Eq. 7, 8, the evolution equation of voids can be obtained in the form:

$$df = (1 - f) d\boldsymbol{\varepsilon}^{p} : \mathbf{I} + \frac{f_n}{s_N \sqrt{2\pi}} \exp\left\{ -\frac{1}{2}\left(\frac{\bar{\varepsilon}_{mis}^{pl} - \varepsilon_N}{s_N} \right)^2 \right\} d\bar{\varepsilon}_{mis}^{pl} . \tag{10}$$

Based on the experimental investigation, Tvergaard and Needleman have concluded the recommended material constants: $\varepsilon_N = 0.1, s_N = 0.3$.

Above all, GTN model include many unknown parameters, including elastic modulus E, Poisson's ratio υ, yield point stress σ_y and damage parameters f_0,f_c,f_n,f_f,q_1,q_2. This paper would get those parameters by means of experiment and inverse finite element method.

A complete implicit Euler strain update algorithm [7] is applied to solve the numerical simulation of GTN model. Aravas [8] and Zhang [9] have proved it by numerical analysis. This paper uses LS-DYNA software and customs probability damage constitutive model, combining UMAT subroutine, to analysis the GTN model and confirm the damage parameters. In addition,the UMAT assumes that $\bar{\varepsilon}_{mis}^{pl} = hsv(1)$ is the accumulated plastic strain of matrix material, while $f = hsv(2)$ is the accumulated void volume fraction[10].

Simulation of Sample Plate

Uniaxial Tensile Experiment

Physical dimensions of the specimen of AA6016 are shown in Fig.1. The specimen was stretched with a speed of 1.0 mm/min in the uni-axial tensile test and the obtained fracture morphology shows that necking phenomenon didn't occur, which can be seen in Fig. 2. So it's reasonable for considering the engineering stress-strain curve as the real stress-strain curve.

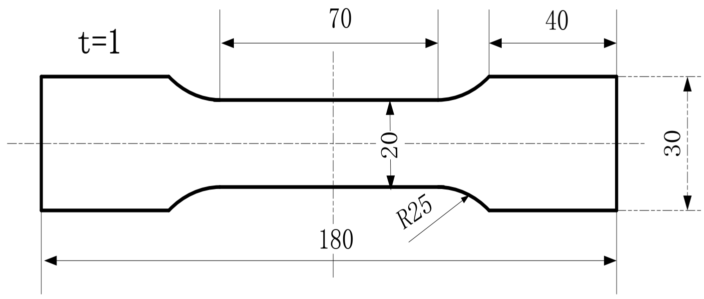

Fig.1 Plate tension specimen

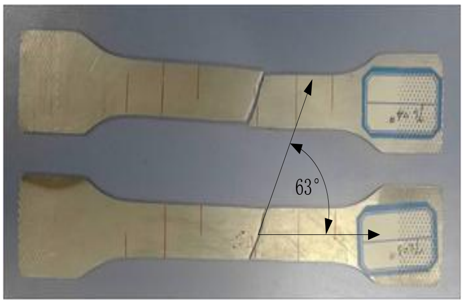

Fig.2 Fracture morphology ofplate tensile specimen

Provided that the void volume fraction f doesn't have any effect on AA6016,the equivalent stress versus equivalent plastic strain response [11, 12] is represented through the following form:

$$\frac{\sigma}{\sigma_y}=\left(\frac{\sigma}{\sigma_y}+\frac{3G}{\sigma_y}\varepsilon^p\right)^N. \tag{11}$$

in this formula,σ_y and σ correspond to the yield stress and the equivalent stress respectively, ε^p represents the plastic strain, G is the shear modulus, and N is the plastic hardening exponent.

Considering the material's stress will increase with the strain without the influence of porosity, fitting Eq. (11) would only depend on the first half part of the experimental data 1 or data 2 which are shown in Fig.3.The fitting results are: the material elastic modulus $E = 61674.38\ MPa$, the Poisson's ratio $\upsilon = 0.3$, the plastic hardening exponent $N = 0.13$, and the yield stress $\sigma_y = 137.3\ MPa$.

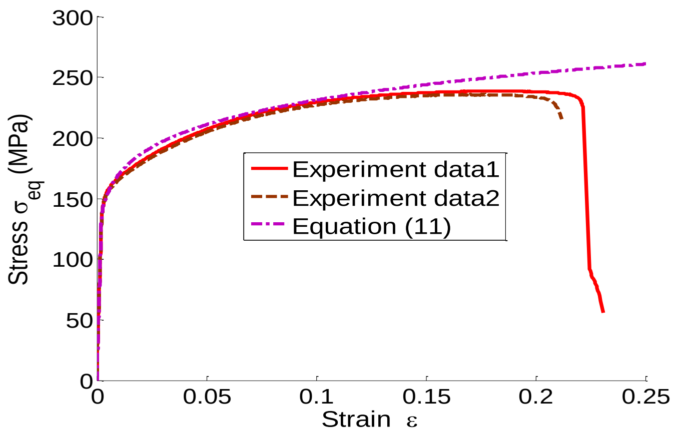

Fig.3 Stress–strain curves of plate tensile specimens

GTN Damage Parameters Identification

On account of AA6016 panel is plastic (extensible) material and its ductile fracture is mainly caused by the growth of voids,it is reasonable to assume the void fusion factor $kk = 1$[13, 14]. According to the analysis given by G. Vadillo.et.al. [15], the hypothesis of damage parametersis made to:$q_2 = 0.8$,$\varepsilon_N = 0.1$,$s_N = 0.3$, GTN parameters such as f_0,f_n,f_f,are obtained from the inverse finite element method[16], and all the parameters are listed in Table 1.

Tab. 1. Parameters of GTN constitutive model.

AA6016	E	υ	σ_y	q_1	q_2
	6167.38	0.3	137.3	1.88	0.8
	ε_N	s_N	f_n	f_0	f_f
	0.3	0.1	0.15	0.001	0.031

The FEM model and boundary condition of AA6016 panelare shown in Fig. 4. Fig.5 shows the distribution contour of the void volume fraction f $(hsv(2))$ that got from the simulation.

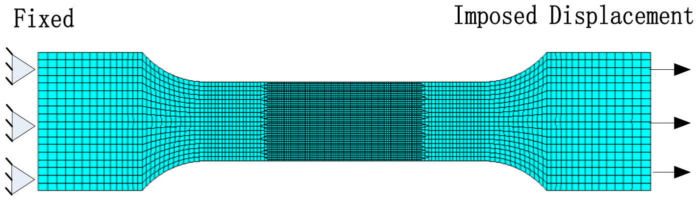

Fig. 4 Boundary Conditions of plate tension specimen

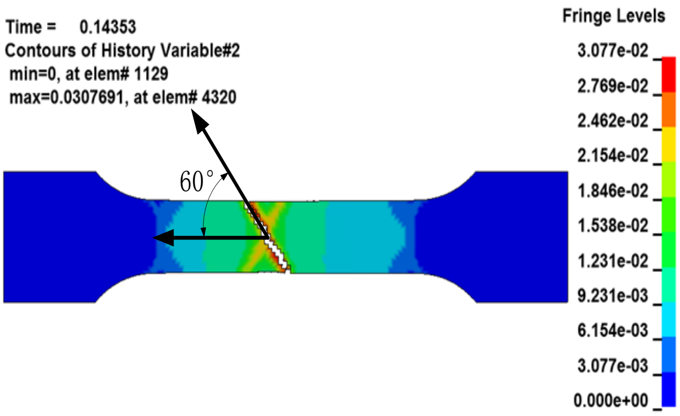

Fig. 5 Void volume fraction *f (hsv(2))* of plate tension specimen

It can be seen that the void volume fraction *f* mainly focus on the surface of the fracture when the plate specimen was broken. The fracture surface versus the DX tensile direction is 60°in FEM simulation(Fig.5),while it is 63° in the experimental result (Fig.2). Thus, the fracture appeared in simulation result is similar to the experimental result. However, previous literatures show that the fracture surface versus the DX tensile direction is 45°or90°,which is not the same with our results.

The tensile stress versus tensile strain relationship of AA6016 are shown in Fig. 6, where '--' represents the pure plastic stress-strain curve (Eq.11), '—' is the experimental result, and 'o' is the simulation result obtained from the GTN model. It is clear that with the increment of plastic strain ε^p, the void volume fraction f imposes an increasing influence on the mechanical behavior of AA6016,and when *f* comes to 3.1e-2 (see Fig.5, Table 1), the failure would occurs. Fig.6 has shown that the curves of the GTN model and the experiment are very similar. Therefore,it indicates that the parameters of the GTN model are applicable for AA6016.

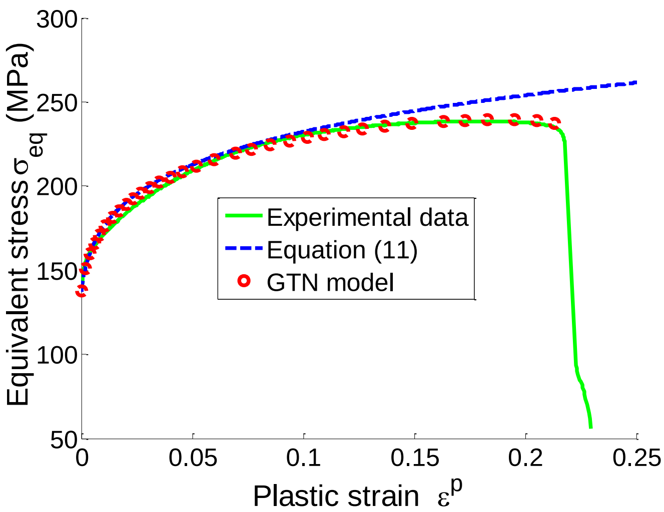

Fig. 6 Contrast of equivalent plastic stress–strain curves

Influence of GTN Damage Parameters on f

The plastic potential state equation Eq. 1 shows that the variation condition of macro equivalent stress in evolution process is similar to that condition of f versus the plastic strain. According to the basic theory of GTN model, the propagation of void volume fraction f includes three main aspects as following:

Firstly, from Eq. 1, it can be seen that when $f \geq f_c$, the void growth acceleration factor kk has great effects on void coalescing. Owing to the previous assumption that $kk = 1.0$, the effect of f_c on the damage of AA6016 is not considered.

Secondly, Eq. 10 is the iterative equation of void volume fraction df, including void nucleation and growth. Due to the relationship of f_n and A_N as shown in Eq. 9, f_n has an influence onA_N. And Fig.7 shows the influence of different values of f_n on the equivalent stress–plastic strain curve. With the growth of f_n, the simulated GTN curve will gradually deviate from the elastic-plastic curve given by Eq. 6. While $f_n = 0.16$, the simulated GTN curve and the experimental curve can match together very well. Furthermore, when $f_n > 0.16$, the simulated GTN curve will gradually deviate from the experimental one. Another phenomenon is shown in Fig.8, when $f_n = 0$, that is the void volume fraction f is nearly 0, and the rate of f versus f_n increases, which will deviate the GTN simulated curve from the elastic-plastic one.

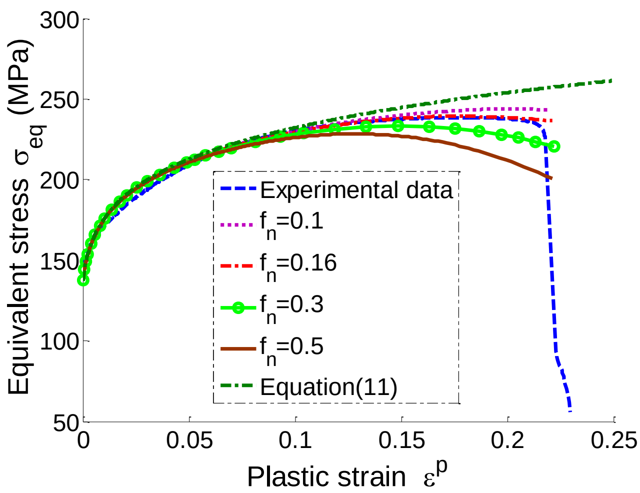

Fig.7 Equivalent stress–plastic strain curves for different $f_n$parameters

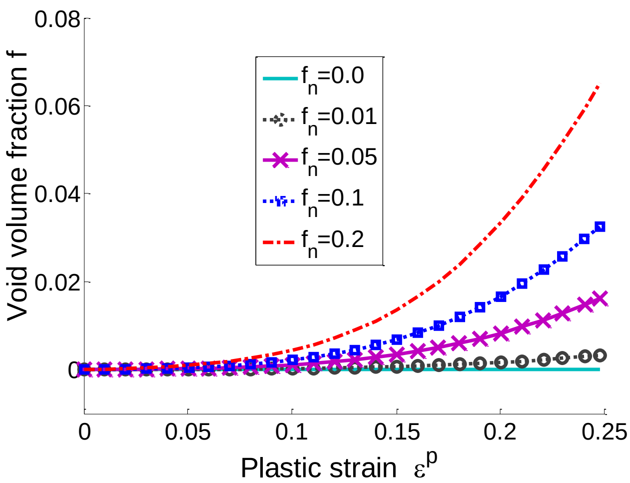

Fig.8 Void volume fraction–plastic strain curves for different f_n parameters

Thirdly, that the initial void volume fraction f_0 is used to depict the voids produced in the manufacturing of roughcast which has an effect on the damage of ductile material in a certain range.

Kim[17] assumed that f_0 ranges from 0.001 to 0.025 for the common material. Therefore,simulations were done by setting the value of f_0 from 0.001 to 0.03 to study the effect on stress-strain curve of AA6016 sheet metal. When f_0 changes in the range of 0 to 0.001, the material mechanical properties will be less affected as shown in Fig.9. While $f_0 > 0.01$, the differences between the experimental curve and the plastic strain curve calculated by simulation will become bigger, which means the effect of f_0 on material stress-strain curve will become bigger as well, and further affects the stamping process of the material. As a result, problems such as crack initiation and nuclear cracking will appear.

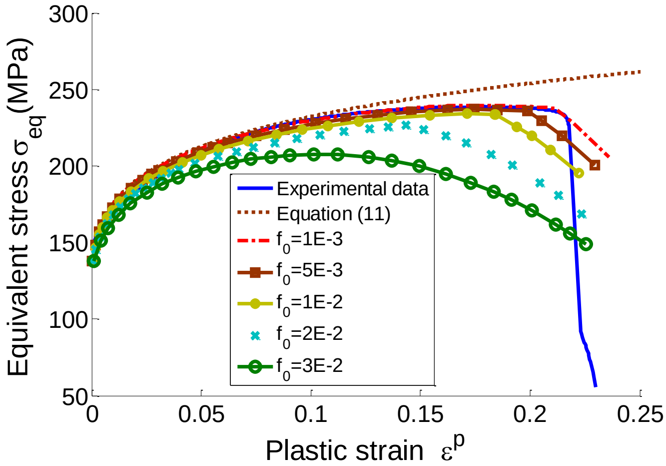

Fig.9 Equivalent stress–plastic strain curves for different f_0 parameters

Results and Discussion

By experiment and inverse finite element method, the parameters of the GTN model for AA6016 sheet metal were finally identified. Meanwhile, the influences of damage parameters f_0 and f_n on the voids evolution progress and the fracture progress were alsodiscussed in this paper. The conclusions are shown as follows:

1)The influence of the f_n in the GTN model on voids evolution shows that it has a distinct effect on fitting the stress-strain curve of AA6016. Though it is widely acknowledged that the GTN model's damage parameter f_n ranges from 0.01 to 0.06, in this investigation, the results of simulation and experiment were in agreement while $f_n = 0.16$. The reason may be that the AA6016 is a super plastic material and the failure strain could reach to 0.21, so that the value of AA6016's damage parameter f_n exceeds the general numeric value.From this aspect it shows that the nucleation coefficient f_n will contribute to the void's evolution progress.

2) Through the research on initial void volume fraction f_0, it is obvious that the initial voids have a wide influence on the mechanical properties of damage and fracture.Fig.9 shows that when f_0 varies from 0.00 to 0.001, it has little influence on the mechanical properties, however, when f_0 exceeds 0.01, the influence becomes greater, and the simulation curve will deviate from the experimental curve more and more. It indicates that the research on f_0 will be helpful in inspecting whether the AA6016 blank is qualified.

Acknowledgements

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