Computational Materials Science 128 (2017) 229–235

Contents lists available at ScienceDirect

Computational Materials Science

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

An extended GTN model for indentation-induced damage

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ARTICLE INFO

Article history:
Received 30 July 2016
Received in revised form 6 October 2016
Accepted 23 November 2016

Keywords:
Voids
Shear
Indentation
Damage

ABSTRACT

The damage of metallic alloys induced by tensile deformation can be well described by Gurson-Tvergaard-Needleman (GTN) model. However, damage growth under intense shear loading, which has been found in micro-/macro-indentation tests, cannot be captured by this model. In this paper, an extension to GTN model is proposed to explain the damage induced by spherical indentation deformation. The nucleation of the secondary voids and the shear softening and localization due to the existing voids are taken into account. An independent law is proposed for the evolution of damage as a function of porosity. An implicit numerical integration using the generalized mid-point algorithm is formulated in the presented paper. Based on the extended GTN model, indentation simulations are performed. It is found that the coexistence of the shear softening and the nucleation of the secondary void mechanism is adequate to explain the damage induced by indentation as a result of the good agreement between the experimental measurement and the simulation prediction.

1. Introduction

Damaged plasticity models have been widely used in the past twenty years in predicting the ductile fracture of engineering structures such as pipelines and nuclear vessels. There are many different constitutive models capable of describing the damage of materials. McClintock [1], Rice and Tracey [2] proposed a model describing the growth of spherical or cylindrical voids. Assuming that the plastic deformation of the matrix material surrounding the spherical voids obeys the J_2 theory, Gurson [3] proposed a phenomenological model which describes the void growth under the influence of mean stress. Based on a bifurcation study, Tvergaard [4] suggested modifying the Gurson's yield criterion by incorporating two additional parameters. In order to account for the rapid drop in stress carrying capacity, Tvergaard and Needleman [5] later on suggested replacing the actual void volume fraction by the effective void volume fraction, i.e. an artificially accelerated void growth. The formulation proposed by Gurson, improved by Tvergaard and Needleman, i.e. the GTN model, is widely used to describe the damage and failure behavior of metallic materials. Within the range of high levels of stress triaxialities where spherical void growth is the predominant mechanism, the GTN model has very good predictive performance.

Recently, several experimental investigations find that indentation deformation may induce noticeable damage to ductile metals manifested by the degradation of the measured elastic modulus at micro/macro scale [6–8]. Considering the indentation is dominated by compressive and shear deformation, no or only insignificant damage would be induced to the ductile materials according to the classical GTN model. In addition, many other studies also find that significant damage may be induced by shear deformation. To account for the damage induced by shear softening, several extensions have been proposed to the classical GTN model through modeling the distortion of the existing voids and/or the nucleation of the secondary voids [9–11]. These extended GTN models predict the failure of ductile materials very well under simple shear tests. However, their performance needs further verifications by more complex tests such as the indentation test where both shear and compressive deformations exist.

The purpose of the present study is to investigate the mechanism for the indentation-induced ductile damage. Firstly, the classical GTN model will be briefly reviewed. The physics for the proposed extensions will be explained. Then finite element simulations on indentation tests will be conducted based on the extended GTN models. The validity of the extensions will be discussed through the comparison between the numerical simulations and experimental measurements.

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http://dx.doi.org/10.1016/j.commatsci.2016.11.043
0927-0256/

2. Gurson-Tvergaard-Needleman model

In order to describe ductile damage and fracture, Gurson [3] proposed a micromechanical model which took into account a strong coupling between damage and plastic strain. Under an assumption of spherical voids uniformly dispersed within a solid with a volume fraction f, the pressure dependent yield condition has been developed in the following form,

$$\varphi(\mathrm{f},p,q) = \frac{q^2}{\sigma_M^2} + 2q_1 f \cosh\left(-\frac{3q_2 p}{2\sigma_M}\right) - 1 - (q_1 f)^2 \tag{1}$$

where p and q are the pressure and the von Mise stress respectively, σ_M donates the flow stress of the matrix material, q_1 and q_2 are material constants and $q_1 = q_2 = 1$ in the original model. This model took into account the interaction between voids and the effect of void growth but the proposed yield surface could not accurately represent the void growth rates and completely neglected the void coalescence.

Based on a bifurcation study, Tvergaard [4] proposed modifying the Gurson yield condition by setting $q_1 = 1.5$ and $q_2 = 1$, q_1 and q_2 allow to describe the void growth kinetics observed in unit cell computation in an accurate way. Tvergaard and Needleman [5] then suggested replacing f by f^* which was defined by the following equation so as to account for the rapid drop in stress carrying capacity.

$$f^* = \begin{cases} f & \text{if } f \leqslant f_c \\ f_c + \frac{1/q_1 - f_c}{f_F - f_c}(f - f_c) & \text{otherwise} \end{cases} \tag{2}$$

where f_c and f_F represent the critical void volume fraction and the void volume fraction at fracture respectively. Void coalescence becomes active when $f \geqslant f_c$. Finally, the yield function proposed by Tvergaard and Needleman was given by:

$$\varphi(f^*,p,q) = \frac{q^2}{\sigma_M^2} + 2q_1 f^* \cosh\left(-\frac{3q_2 p}{2\sigma_M}\right) - 1 - (q_1 f^*)^2 \tag{3}$$

The evolution of the void volume fraction f is given by the sum of the void nucleation and the void growth:

$$\dot{f} = \dot{f}_{nucleation} + \dot{f}_{growth} \tag{4}$$

Chu and Needleman [14] assumed that stress or strain controlled void nucleation mechanism follows a normal distribution. The rate of void nucleation was defined on the rate of the equivalent plastic strain of the matrix material $\dot{\varepsilon}_M^{pl}$

$$\dot{f}_{nucleation} = A_N \dot{\varepsilon}_M^{pl} \tag{5}$$

where $A_N = \frac{F_N}{s_N\sqrt{2\pi}} \exp\left(-\frac{1}{2}\left(\frac{\varepsilon_M^{pl} - \varepsilon_N}{s_N}\right)^2\right)$, ε_N and s_N are the mean value and standard deviation of the strain, F_N the void nucleating particles fraction.

Since the matrix material is supposed to be plastically incompressible, the void growth rate can be defined by

$$\dot{f}_{growth} = (1-f)\dot{\boldsymbol{\varepsilon}}^{\boldsymbol{pl}} : \boldsymbol{I} \tag{6}$$

where $\dot{\boldsymbol{\varepsilon}}^{\boldsymbol{Pl}}$ donates the rate of macroscopic plastic strain tensor and $\boldsymbol{I}$ the second-order identity tensor, $\dot{\boldsymbol{\varepsilon}}^{\boldsymbol{Pl}} : \boldsymbol{I}$ signifies the trace of strain tensor which depicts the rate of volume change. $\dot{\boldsymbol{\varepsilon}}^{\boldsymbol{pl}}$ can be calculated by the normality flow rule

$$\dot{\boldsymbol{\varepsilon}}^{\boldsymbol{pl}} = \dot{\lambda}\frac{\partial\varphi}{\partial\boldsymbol{\sigma}} \tag{7}$$

where $\boldsymbol{\sigma}$ is the stress tensor and λ the plastic multiplier. The rate of the matrix plastic strain can be obtained by considering the plastic work:

$$\dot{\boldsymbol{\varepsilon}}_{\boldsymbol{pl}} : \boldsymbol{\sigma} = (1-\mathrm{f})\ \sigma_M \dot{\varepsilon}_M^{pl} \tag{8}$$

3. Extension to the GTN model

The above formulated GTN (Gurson-Tvergaard-Needleman) model predicts no damage nucleation or growth under zero or negative mean stress [15]. To describe the damage and failure due to shear deformation, pioneering work has been conducted to model the mechanism of shear softening [9–13]. These models have shown great improvement in predicting the damage and failure of ductile materials, especially in the case of simple shear loading. However, none of them has coupled the damage with the degradation of elasticity and as a consequence, the degradation of elasticity by indentation deformation cannot be captured. In the present study, an extension is proposed to take the degradation of elasticity into account. It is worth noting that in the extended GTN model, the damage is defined directly by the effective void volume fraction.

3.1. Lode angle dependence

In order to describe the combined stress state, a new parameter called Lode angle, which represents the third stress invariant on the octahedral plane, has originally been introduced by Xue [10]. In the presented paper, the Lode angle function g, proposed by Xue, is used:

$$g = 1 - \frac{6}{\pi}|\tan^{-1}\left(\frac{1}{\sqrt{3}}\left(2\left(\frac{s_2 - s_3}{s_1 - s_3}\right) - 1\right)\right) \tag{9}$$

where s_1, s_2, s_3 denote the three principal deviatoric stress components and $s_1 > s_2 > s_3$. The value of g can vary from 0 to 1: $g = 0$ for tensile stress state, $g = 1$ for pure shear state and $0 < g < 1$ for combined stress state.

3.2. Second-phase nucleation mechanism

The nucleation of the primary voids is described by Eq. (5). However, this strain rate controlled primary voids nucleation mechanism is inadequate to describe the void nucleation due to the second-phase particles. In order to consider void sheeting and localization under shear condition, a new independent nucleation mechanism is proposed by Malcher [11] using the same formulation as Chu and Needleman [14]:

$$\dot{h}_{nucleation} = A'_N \dot{\varepsilon}_M^{pl} \tag{10}$$

where $A'_N = \frac{F'_N}{s'_N\sqrt{2\pi}} \exp\left(-\frac{1}{2}\left(\frac{\varepsilon_M^{pl} - \varepsilon'_N}{s'_N}\right)^2\right)$, ε'_N and s'_N are the mean value and standard deviation of the second population of void nucleation strain, F'_N is the secondary void nucleating particles fraction.

Thus, the total nucleation contains two contributions. The first part represents the evolution of the primary void volume fraction as depicted by Eq. (5) and the second part represents the evolution of the secondary void volume fraction induced by shear effect as depicted by Eq. (10).

3.3. Shear softening and localization mechanism

Void growth and coalescence can be accelerated by shear softening and localization. With an assumption that the volume of voids remains constant, Xue [10] proposed an additional term to describe the equivalent growth of voids due to the shear softening and localization. The additional term proposed by Xue is formulated as

$$\dot{h}_{growth} = q_3 f^{q_4} \varepsilon_{eq} \dot{\varepsilon}_{eq} \tag{11}$$