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Modeling the ductile damage process in commercially pure titanium

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ABSTRACT

This paper presents a constitutive model, which combines the models proposed by Stewart and Cazacu (2011) and Zhou et al. (2014), to describe the ductile damage process in a commercially pure titanium (CP Ti) and to simulate its mechanical response. In particular, a Gurson-type porous material model is modified by coupling two damage parameters, accounting for the void damage and the shear damage respectively, into the yield function and the flow potential. The plastic anisotropy and tension–compression asymmetry exhibited by CP Ti are accounted for by a plasticity model based on the linear transformation of the stress deviator. The theoretical model is implemented in the general purpose finite element software ABAQUS via a user defined subroutine and calibrated using experimental data. Good comparisons are observed between model predictions and experimental results for a series of specimens in different orientations and experiencing a wide range of stress states.

1. Introduction

Titanium and its alloys have found widespread use in both commercial and industrial applications because of their outstanding engineering properties, such as good corrosion resistance, high strength to weight and stiffness to weight ratios, good toughness, low density, desirable formability, and biocompatibility (Hanson, 1986). Commercially pure titanium (CP Ti) is considered in this study. CP Ti has a hexagonal closed packed (hcp) crystal structure at room temperature. Hcp dominated metals are known to display plastic anisotropy and have a strong strength differential in tension and compression (i.e., non-symmetry between tensile and compressive strengths). This is because two types of deformation modes, slip and/or twinning, can occur in the hcp crystal structure during plastic deformation. It is generally agreed that the strong strength differential is associated with the activation of twinning (Chun et al., 2005; Salem et al., 2003; Hosford and Allen, 1973).

In order to design structures or mechanical components that seek to optimize weight, efficiency, and strength while maintaining safety, it is important to consider the evolution of damage within the material in question. In the particular case of ductile materials, modeling the progressive internal material degradation and failure process has been the focus of extensive research efforts over the past several decades. Gurson (1977) proposed a widely used homogenized yield criterion for void-containing materials based on the maximum plastic work principle, where the matrix material is assumed to obey the von Mises isotropic yield criterion. More recent efforts have been focused on extending/modifying the Gurson model to develop computational schemes that simulate the ductile fracture process under various circumstances. Tvergaard (1981,1982) introduced two adjustment parameters into the Gurson model to account for the effect of void interaction and material strain hardening. Chu and Needleman (1980) proposed void nucleation models controlled by the local stress or plastic strain. Tvergaard and Needleman (1984) introduced a simplified method to provide for rapid deterioration of stiffness after localization has occurred in the material. The Gurson model, with the additional development by Tvergaard and Needleman, is often referred to as the GTN model by the fracture mechanics community. Gologanu et al. (1993,1994) derived a yield function for materials containing prolate and oblate voids. This model reduces to the form of the Gurson model when the void shape remains spherical. Gao et al. (2011) postulated to extend the Gurson model to include the effects of hydrostatic stress and the third invariant of stress deviator on the matrix material. Benzerga and Besson (2001) extended the Gurson model for orthotropic materials and later Benzerga et al. (2004) proposed a yield criterion which accounts for the effects of both void shape and material orthotropy. Recently Stewart and Cazacu (2011) developed a macroscopic anisotropic yield

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criterion for porous materials when the matrix material is incompressible, anisotropic and displays tension–compression asymmetry. This model degenerates to the form of the Gurson model when the matrix material obeys the von Mises plasticity theory. For the Gurson-type models, the prediction of ductile fracture comes out naturally through the progressive loss of load carrying capacity at the material level.

Despite the apparent success and wide popularity of the Gurson-type models in predicting ductile fracture, a major drawback is their inapplicability to model localization and fracture under low stress triaxiality, shear dominated deformations since these models do not predict void growth and damage evolution under shear loading. Under low stress triaxiality, rather than void growth, shear localization becomes the mechanism of ductile fracture (Rice, 1976; Yamamoto, 1978; Mear and Hutchinson, 1985; Barsoum and Faleskog, 2007; Mohr and Marcadet, 2015). To overcome this problem, Xue (2008) and Nahshon and Hutchinson (2008) modified the GTN model (Gurson, 1977; Tvergaard, Needleman, 1984) by treating the void volume fraction in the model as a generalized damage parameter which includes the shear damage contribution. Nielsen and Tvergaard (2009) modified the Nahshon–Hutchinson model by pre-multiplying the shear damage contribution by an ad hoc triaxiality-dependent factor to improve the model performance in the medium to high triaxiality region. Zhou et al. (2014) discussed the issues of using a single damage parameter in the GTN yield function and presented a modified model by combining the damage mechanics concept of Lemaitre (Lemaitre, 1985) with the Gurson-type porous plasticity model. Malcher et al. (2014) proposed an extended GTN model, which has two independent damage parameters: the first one is driven by the hydrostatic stress and the second other is driven by the deviatoric stress. Jiang et al. (2016) modified the GTN model in a similar way to study the ductile fracture behavior under high, low and negative stress triaxiality loadings, in which two distinctive damage parameters, respectively related to void growth mechanism and void shear mechanism, are introduced into the yield function as internal variables of the degradation process. In all these modified GTN models, the matrix material is always treated as isotropic.

In this work, we combine the models of Stewart and Cazacu (2011) and Zhou et al. (2014) to describe ductile damage evolution in CP Ti. The structure of the paper is as follows. In Section 2, the ductile damage model, which include both void damage and shear damage, and the matrix plasticity model, which accounts for both plastic anisotropy and tension–compression asymmetry, are described. The evolution law for void volume fraction remains the same as in the original GTN model and the shear damage evolution law proposed by Xue (2008) is adopted. Section 3 describes the material, test matrix and experimental procedure. Section 4 details the model calibration procedures and Section 5 compares the model predictions with experimental results. Finally some concluding remarks are given in Section 6.

2. The ductile damage model

Ductile fracture is usually attributed to a process of void nucleation, growth and coalescence under triaxial stress state (McClintock, 1968; Rice and Tracey, 1969; Van Stone et al., 1985; Garrison Jr. and Moody, 1987) and a process due to shear localization when the stress triaxiality becomes low (Rice, 1976; Yamamoto, 1978; Mear and Hutchinson, 1985; Barsoum and Faleskog, 2007; Mohr and Marcadet, 2015). One of the most widely used micromechanical models for ductile fracture is due to Gurson with subsequent development by Tvergaard and Needleman (Gurson, 1977; Tvergaard and Needleman, 1984). The yield function of the GTN model takes the following form

$$\Phi = \left(\frac{\sigma_e}{\sigma_M}\right)^2 + 2q_1 f \cosh\left(\frac{q_2}{2}\frac{\sigma_{kk}}{\sigma_M}\right) - 1 - (q_1 f)^2 = 0, \tag{1}$$

where f is the current void volume fraction, σ_e is the macroscopic effective stress, σ_{kk} is the hydrostatic stress, and σ_M is the current yield stress of the matrix material. The adjustment parameters q_1 and q_2 were introduced by Tvergaard (1981, 1982) to improve model predictions. The evolution of the void volume fraction is given by

$$\dot{f} = \dot{f}_{\text{growth}} + \dot{f}_{\text{nucleation}} \tag{2}$$

where $\dot{f}_{\text{growth}}$ and $\dot{f}_{\text{nucleation}}$ represent the growth and nucleation of the voids. Evaluation of the void growth rate is based on the bulk material incompressibility under plastic deformation

$$\dot{f}_{\text{growth}} = (1-f)\dot{\varepsilon}^p_{kk} \tag{3}$$

where $\dot{\varepsilon}^p_{kk}$ represents the first invariant of the plastic strain rate tensor, which defines the rate of volume change. Void nucleation can be stress or strain controlled. A commonly used strain controlled void nucleation law follows a normal distribution in a statistical way as suggested by Chu and Needleman (1980)

$$\dot{f}_{\text{nucleation}} = A_N \dot{\varepsilon}^p_M, \quad A_N = \frac{f_n}{S_n\sqrt{2\pi}}\exp\left[-\frac{1}{2}\left(\frac{\varepsilon^p_M - \varepsilon_n}{S_n}\right)^2\right] \tag{4}$$

where ε^p_M represents the matrix plastic strain, S_n and ε_n are the standard deviation and the mean value of the distribution of the plastic strain, and f_n is the total void volume fraction that can be nucleated. Parameters f_n, ε_n and S_n can be treated as material constants.

The effect of rapid void coalescence after the onset of localization is taken into account by replacing f in Eq. (1) with an effective porosity f^* defined by the following bilinear function (Tvergaard and Needleman, 1984)

$$f^* = \begin{cases} f & \text{for } f \le f_c \\ f_c + \frac{1/q_1 - f_c}{f_f - f_c}(f - f_c) & \text{for } f_c \le f \le f_f \end{cases} \tag{5}$$

where f_c is the critical void volume fraction at which void coalescence begins and the material softening is accelerated thereafter. As f reaches f_f, the material loses all stress carrying capacity.

In the original GTN model, the matrix material obeys the J_2 flow plasticity theory, where σ_e is the von Mises equivalent stress. Stewart and Cazacu (2011) extended GTN model to account for the plastic anisotropy and tension–compression asymmetry exhibited by the matrix material. The macroscopic yield criterion of this extended model is expressed as

$$\Phi = \left(\frac{\sigma_e}{\sigma_M}\right)^2 + 2q_1 f \cosh\left(\frac{q_2}{h}\frac{\sigma_{kk}}{\sigma_M}\right) - \left(1 + q_1 f^2\right) = 0 \tag{6}$$

where h is a material parameter depending on the anisotropy coefficients as well as the strength differential coefficient and σ_e is defined by Eq. (7). Here the plasticity model developed by Cazacu et al. (2006) is adopted to describe the matrix plasticity behavior. This model is based on a linear transformation of the deviatoric part of the Cauchy stress tensor, similar to previous studies by Barlat and coworkers (Barlat et al., 1991, 1997) and Lademo et al. (1999). The yield condition of this plasticity model is expressed as

$$\begin{gathered}\sigma_e(\Sigma_i, k) = \sigma_M \\ \sigma_e = m\sqrt{(|\Sigma_1| - k\Sigma_1)^2 + (|\Sigma_2| - k\Sigma_2)^2 + (|\Sigma_3| - k\Sigma_3)^2}\end{gathered} \tag{7}$$

with