Mechanics of Materials 40 (2008) 685–694

Contents lists available at ScienceDirect

Mechanics of Materials

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

Elastoplastic characterization and damage predictions under evolving local triaxiality: axysimmetric and thick plate specimens

G. Mirone *

Dipartimento di Ingegneria Industriale e Meccanica, Università di Catania, Vl.e A. Doria 6, 95125 Catania, Italy

ARTICLE INFO

Article history:
Received 17 July 2007
Received in revised form 3 March 2008

Keywords:
Elastoplasticity
True stress
Necking
Stress triaxiality
Ductile damage

ABSTRACT

Ductile failure is a phenomenon involving large plastic strains, thus any method for predicting fracture of mechanical components needs to be supported by a reliable procedure for the material stress–strain characterization, whose accuracy is an essential prerequisite for allowing any damage model to deliver accurate predictions.

Sometimes the true stress–true strain curves from smooth tensile specimens are used in the literature for identifying a metal despite their low accuracy at the post-necking deformation levels, but usually the experimental true stress is corrected by the Bridgman factor for the necking effect. Two mathematical models, of the stress–strain characterization in the elastoplastic post-necking phase and of the ductile failure prediction, are used in this paper for a FE 370 carbon steel.

The stress–strain data accounting for the necking-induced triaxiality and the critical value of a damage indicator based on the cumulated stress triaxiality are obtained by applying the model called MLR and the Bao–Wierzbicki model, respectively, to experimental data from tensile tests on smooth and notched specimens. Then, the acquired data are used to simulate the material behavior with reference to two series of differently notched plate specimens. Simulated behavior is then compared with experiments for evaluating the achieved degree of accuracy.

1. Introduction

Prediction of ductile failure can be divided into a sequence of three logical steps by determining the material hardening functions, then calculating the stress and strain fields on the structure subjected to the known loads and constraints (usually by finite elements, FE), and finally by assessing the compatibility of the applied stress–strain history with the material ability to withstand ductile damage.

In the case of a monotonic loading, the von Mises equivalent stress σ_{eq} related to the equivalent plastic strain ε_{eq} constitutes the isotropic hardening function and its knowledge is sufficient to define the stress–strain elastoplastic behavior of metals. The measurement of the two above variables from experimental data is very simple only when tensile specimens have uniform cross-section (so that σ_{eq} coincides with the true stress σ_t which is the ratio between load and cross-section), but becomes virtually impossible when necking occurrence, affecting about 60–99% of the straining history of a ductile metal, induces cross-sections variability along the specimen axis. The Bridgman model (Bridgman, 1956; Alves and Jones, 1999) is the most used in the literature for evaluating the equivalent stress in the post-necking phase by introducing corrections to the true stress and the model by Zhang et al. (1999) improves the Bridgman predictions for specimens with rectangular cross section, but a simpler and more accurate procedure, called MLR from the name of the team that proposed it in La Rosa et al. (2003), Mirone (2004), is used in this paper.

The calculation of stress and strain histories at each material point of a component or a structure is relatively simple with the help of FE commercial codes which currently provide good results in integrating von Mises

* Tel.: +39 095 7382418.
E-mail address: gmirone@diim.unict.it

0167-6636/$ - see front matter © 2008 Elsevier Ltd. All rights reserved.
doi:10.1016/j.mechmat.2008.03.004

plasticity with large displacements and finite strains, provided that material data, mesh and boundary conditions are sufficiently accurate in representing the real phenomenon. The third step, for verifying whether the stress and strain histories from FE are effectively sustainable by the material or not, implies the adoption of a damage model and a failure criteria.

Various models have been proposed in the literature, all based on the experimental evidence that ductile damage consists of the nucleation, growth and coalescence of microvoids or of shear banding instability, one or the other mechanism depending on the range in which the stress triaxiality evolves during the strain history (McClintock, 1968; Rice and Tracey, 1969; Mackenzie et al., 1977; Hancock and Mackenzie, 1976; Mirone, 2004).

The majority of damage models can be grouped in the three families of continouus damage mechanics (CDM) originally due to Lemaitre and Chaboche (Lemaitre, 1985; Chaboche, 1988; Bonora, 1997; Wang, 1992; La Rosa et al., 2001), of the Gurson–Tvergaard–Needleman or GTN theory (Gurson, 1977; Tvergaard and Needleman, 1984; Needleman and Tvergaard, 1984; Ragab, 2004), and of the Rice–Tracey or energy based models (Le Roy et al., 1981; Schiffmann et al., 2003; Chaouadi et al., 1994; Alves and Jones, 1999).

The first and the last of the above approaches are uncoupled by the FE integration while the GTN approach is necessarily coupled to the FE because, in this case, the evolving void volume fraction representing the damage variable induces continuous modifications of the yield surface during a strain history.

Recently, Bao and Wierzbicki proposed a simple model (Bao and Wierzbicki, 2004; Bao and Wierzbicki, 2004; Mirone, 2007) by assuming the cumulative triaxiality as a damage indicator which exhibits a material-constant critical value at high stress triaxiality; this model is of simple implementation due to the uncoupling postulated between the damage variable and the yield surface, and the results it provides in predicting failure are very promising with respect to other CDM or energy-based uncoupled models.

1.1. Modeling post-necking behavior and damage evolution

When a ductile metal is subjected to monotonically increasing plastic strain, the kinematic hardening is usually neglected and the isotropic hardening alone, in the form of the function $\sigma_{eq}(\varepsilon_{eq})$ relating the equivalent stress to the equivalent plastic strain, is used to describe the stress–strain behavior. The hardening function corresponds to a set of points $(\sigma_{eq}, \varepsilon_{eq})$ whose coordinates are calculated from measurements at different instants of a tensile test. For a generic stress state, the equivalent stress and the equivalent plastic strain expressed in the principal coordinate system are

$$\begin{aligned} \sigma_{eq} &= \sqrt{\frac{1}{2}[(\sigma_1-\sigma_2)^2+(\sigma_1-\sigma_3)^2+(\sigma_2-\sigma_3)^2]}, \\ \varepsilon_{eq} &= \sqrt{\frac{2}{9}[(\varepsilon_1-\varepsilon_2)^2+(\varepsilon_1-\varepsilon_3)^2+(\varepsilon_2-\varepsilon_3)^2]}. \end{aligned} \tag{1}$$

For correlating σ_{eq} to ε_{eq}, smooth round tensile specimens are often used so that the stress state is uniform and uniaxial all over the gauge section; the z, r, θ principal coordinate cylindrical system has z along the specimen axis, r radial abscissa and θ angular coordinate. By placing the origin at the center of the studied cross-section the z coordinate is set to zero, and given the axial symmetry it is possible to neglect the θ coordinate, so the only remaining geometric variable is the radial coordinate r.

When a stress state is uniaxial in the z direction, the stress tensor has a component alone and σ_{eq} coincides with σ_z as in the following equation:

$$\tilde{\sigma}(r) = \begin{bmatrix} \sigma_z(r) & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix} \Rightarrow \sigma_{eq}(r) = \sigma_z(r). \tag{2}$$

If a function is uniformly distributed over its domain, then its average value is obviously coincident with the local values, and for σ_z this leads to the equation

$$\sigma_z(r) = \sigma_z = \frac{F}{\pi a^2} = \sigma_t, \tag{3}$$

with F and a the current load and the current cross-section radius, respectively. The load/cross-section ratio in Eq. (3) is the section-averaged axial stress conventionally called true stress σ_t.

When the stress state is at the same time uniaxial and uniform, both (2) and (3) apply and the equivalent stress at all material points can be expressed in terms of measurable quantities by

$$\sigma_{eq}(r) = \sigma_{eq} = \sigma_z = \sigma_t = \frac{F}{\pi a^2}. \tag{4}$$

The plastic strains induced by the above stress state are uniform too, and the volume constancy ($\varepsilon_z + \varepsilon_r + \varepsilon_\theta = 0$) imposed to uniform strains yields a simple differential equation whose solution gives the radial displacement and, in turn, the strain values expressed in the equation

$$\tilde{\varepsilon}(r) = \tilde{\varepsilon} = \begin{bmatrix} 2Ln\frac{a_0}{a} & 0 & 0 \\ 0 & -Ln\frac{a_0}{a} & 0 \\ 0 & 0 & -Ln\frac{a_0}{a} \end{bmatrix}, \tag{5}$$

where a_0 is the radius of the initially undeformed cross-section.

By substituting the strains of (5) into second equation of (1) derives that the equivalent plastic strain can be expressed in terms of measurable quantities and coincides with the axial strain and the logarithmic strain, conventionally called true strain ε_t:

$$\varepsilon_{eq}(r) = \varepsilon_{eq} = \varepsilon_z = \varepsilon_t = 2Ln\frac{a_0}{a}. \tag{6}$$

For smooth specimens before necking, complying with both the requirements of uniaxiality and uniformity of the stress, Eqs. (4) and (6) apply thus the elastoplastic characterization is a simple experimental procedure.

As soon as the necking initiates the stress state becomes increasingly non-uniform and triaxial, so that an initially smooth specimen becomes somehow similar to a notched specimen whose notch severity evolves during the test, up to failure. Then, during the post-necking phase of a tensile test, constituting the greater part of the whole test for ductile metals, it is not possible to obtain a reasonable