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Calibration and evaluation of a combined fracture model of microvoid growth that may compete with shear in the polycrystalline microstructure by means of evolutionary algorithms

J. Jackiewicz *

Department of Mechanical Engineering, University of Technology and Life Sciences, Prof. Kaliskiego 7, PL 85-796 Bydgoszcz, Poland

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ABSTRACT

Changes of stress or strain ratios during an operation can have an effect on cracking during metalworking processes. Therefore, there is a substantive interest of the aluminum and steel industries of the manufacturing sectors in numerical simulations of the fracture processes of typical structural materials. In this paper, a calibration procedure of material parameters for a combined fracture model of microvoid growth that may compete with shear in the polycrystalline microstructure is described. The paper then proceeds to evaluating the probability of structural failure on the basis of the combined fracture model according to the calibrated material parameters. An assessment of the probability of structural failure is important to improve the quality of manufacturing processes, but also to reduce their costs.

1. Introduction

Firstly, the motivation of the present contribution is to establish a detailed calibration procedure of material parameters for a combined fracture model of microvoid growth that may compete with shear in the polycrystalline microstructure. The assumed combined fracture model is hierarchically arranged according to the structure of the material. Moreover, this model is related to the common fracture criteria that give an assessment chance of the occurrence probability of one of physical modes of fracture, namely (i) shear fracture; (ii) material interface decohesion; and (iii) reduction in material strength caused by the presence of the tensile hydrostatic stress that may lead to the brittle mode of fracture or to the ductile damage evolution. Therefore, the various competitive physical modes of fracture can be taken into consideration, from which the

* Tel.: +48 52 340 8252; fax: +48 52 340 8250.
E-mail address: jacek.jackiewicz@mail.utp.edu.pl.

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only one with the greatest fracture likelihood determines the overall fracture limit. A set of experimental tests is taken as a reference to the calibration procedure in the inverse problem. The inverse problem considered in this paper (where the values of model parameters must be obtained from the observed data) is reduced to solving the combinational optimization problem of a joint probability density function. The joint probability density function is constructed by means of individual probability density functions associated to the only one variable material parameter while the other estimated material parameters are prescribed. Each of these individual probability density functions is selected according to an a posteriori error covariance estimate via the Kalman filter. To find the best set of material parameters for the combined fracture model, or in another words to solve the combinatorial optimization problem, one of the evolution strategies (ESs) is implemented.

Secondly, the motivation of the present contribution is to evaluate the probability of structural failure on the basis of the combined fracture model with the previously calibrated material parameters. Evolutionary algorithms well match to this kind of computer simulations because in evolutionary searching across the problem space the members of a population of random parameters in reliability analysis adapt to their environment in order to find the fracture mode with the greatest likelihood. The evaluation of the probability of structural failure is helpful to improve the safety and quality of inelastic structures, but also to reduce the costs of their manufacturing processes.

The organization of this paper is as follows. Section 2 reviews briefly the phenomenological fracture criteria of the maximum shear stress and Wilkins types. Section 3 describes the micromechanical models for the simulation of ductile fracture. Section 4 summarizes the rate-independent constitutive model of a cohesive interface. Section 5 describes the Kalman filtering algorithm, which is used in an inverse problem. Section 6 describes the assessment of the joint probability density function, which is applied to find the most accurate estimation of material parameters in the inverse problem by an evolution strategy. Section 7 presents searching the extremum of the objective function with the evolution strategy. In Section 8, a comparison between experimental and numerical results in order to calibrate the Gurson model is given. Section 9 concludes this paper with a short summary.

2. Phenomenological fracture criteria of the maximum shear stress and Wilkins types

The damage behavior depends strongly on the loading type (stress triaxiality) and cannot be modeled with simple damage models based on one constant fracture strain. Experimental observations [1] indicate that stress triaxiality is not enough to fully describe ductility because multiple stress states with different principal stress values can result in the same stress triaxiality ratio. Therefore, to quantify any stress state the use of the stress triaxiality parameter, $h_{\mathrm{T}} \equiv \sigma_{\mathrm{h}}/\sigma_{\mathrm{eq}}$, and the Lode parameter, $\mu_{\mathrm{L}} \equiv (2\sigma_2 - \sigma_2 - \sigma_3)/(\sigma_1 - \sigma_3)$ (where σ_1, σ_2 and σ_3 are the principal stresses with $\sigma_1 \geqslant \sigma_2 \geqslant \sigma_3$), is postulated. The stress triaxiality parameter, h_{T}, is a ratio of the mean stress, $\sigma_{\mathrm{h}} \equiv \frac{1}{3}\mathrm{tr}(\sigma)$, to the equivalent stress, σ_{eq}. The Lode parameter, μ_{L}, plays the role of a deviatoric state parameter and is related to the third invariant of the stress deviators, $J_3 \equiv \sigma_1^{(\mathrm{dev})}\sigma_2^{(\mathrm{dev})}\sigma_3^{(\mathrm{dev})}$ (where $\sigma_i^{(\mathrm{dev})} \equiv \sigma_i - \sigma_h$ for $i = 1, 2, 3$):

$$\mu_{\mathrm{L}} = \frac{27}{2}\frac{J_3}{\sigma_{\mathrm{eq}}^3}. \tag{1}$$

It is worth to note that Clausmeyer et al. [2] proposed the multiaxial quotient $q_{\mathrm{C}} \equiv 1/(\sqrt{3}h_{\mathrm{T}})$, which indicates the cleavage possibility when a value of q_{C} is less than its critical value for a given material, q_{cleavage}:

$$q_{\mathrm{C}} < q_{\mathrm{cleavage}}. \tag{2}$$

Criterion (2) should be complemented by the yield criterion: $\tau_{\mathrm{re}} = \tau_{\mathrm{yield}}$, where τ_{re} is the representative shear stress and τ_{yield} is yield stress in shear.

To predict the damage behavior an evaluation chain including material characterization, numerical simulation with a suitable damage model and verification by component test was established. In this work, the Gurson model and the Wilkins model have been applied to describe the damage behavior failure in computer simulations. Phenomenological damage models like the Wilkins model and micromechanical models like the Gurson model describe the influence of stress triaxiality on damage development. To model failure along the grain boundaries a rate-independent constitutive model of the cohesive interface [3] is applied.

The maximum shear stress fracture criterion not only follows the trend of experimental points with an accuracy of the engineering type but requires only one test for calibration. Therefore this criterion is used here to calibrate the more universal fracture criterion of the Wilkins type, which requires more experimental tests.

2.1. Maximum shear stress fracture criterion

The ductile fracture may occur on an element plane where the shear stress $\tau_{\max}$ reaches a maximum critical value $\tau_{\max\,\mathrm{F}}$:

$$\tau_{\max} = \tau_{\max\,\mathrm{F}}, \tag{3}$$

where $\tau_{\max} = \max((\sigma_1 - \sigma_2)/2, (\sigma_2 - \sigma_3)/2, (\sigma_3 - \sigma_1)/2)$. Criterion (3) is similar in form to the Tresca yield condition but in general $\tau_{\max\,\mathrm{F}}$ is larger than the yield stress in shear τ_{yield}.

The maximum shear stress fracture criterion may be expressed in terms of strain quantities. For the experimental plane stress in accordance with

1. Hill's quadratic yield criterion for planar isotropic materials, under plane stress conditions

$$\sigma_{\mathrm{eq}}^2 = \sigma_1^2 + a_M\sigma_1\sigma_2 + b_M\sigma_2^2, \tag{4}$$

where a_M and b_M are constants obtained from the strain ratios measured in the uniaxial tension test, and given by the expressions: $a_M \equiv -2\bar{r}/(1+\bar{r})$ in which$\bar{r} \equiv (r_0 + 2r_{45} + r_{90})/4$ (with $r_{0,45,90}(=\varepsilon_{\mathrm{w}}/\varepsilon_{\mathrm{T}})$ along 0°, 45°, and 90° direction,where ε_{w} is the width strain and ε_{T} is the thickness strain), and $b_M = 1$;

2. the associate flow rule

$$\frac{\mathrm{d}\varepsilon_1}{2\sigma_1 + a_M\sigma_2} = \frac{\mathrm{d}\varepsilon_2}{2b_M\sigma_2 + a_M\sigma_1} = \frac{\mathrm{d}\varepsilon_3}{-(2+a_M)\sigma_1 - (2b_M + a_M)\sigma_2} = \frac{\mathrm{d}\varepsilon_{\mathrm{eq}}}{2\sigma_{\mathrm{eq}}}; \tag{5}$$

3. an equivalent strain function of the form

$$\mathrm{d}\varepsilon_{\mathrm{eqv}}^2 = \frac{4}{4b_M - a_M^2}(b_M\mathrm{d}\varepsilon_1^2 - a_M\mathrm{d}\varepsilon_1\mathrm{d}\varepsilon_2 + \mathrm{d}\varepsilon_2^2); \tag{6}$$

4. an assumption of a linear proportional strain path

$$\mathrm{d}\varepsilon_1/\mathrm{d}\varepsilon_2 = \varepsilon_1/\varepsilon_2 = \text{constant}; \tag{7}$$

and

5. a hardening law

$$\sigma_{\mathrm{eq}} = K_M\varepsilon_{\mathrm{eq}}^{n_M}, \tag{8}$$

where n_M is the strain hardening exponent and K_M is the corresponding strength constant; the principal stresses σ_1 and σ_2 are given by