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Calibration and application of ductile fracture criterion under non-proportional loading condition

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ABSTRACT

Two series of experiments were designed and carried out to evaluate the performance of the selected ductile fracture criterion, of which one is the experiments under monotonic loading conditions and the other is the experiments under non-proportional loading conditions. Combined with parallel numerical simulations, the experiments under monotonic loading conditions were utilized to identify the parameters of the fracture criterion with two calibration methods, a conditional one applying several experiments to calculate material constants and an optimization one of surface fitting. The prediction accuracy of fracture related state variables by using the ductile fracture criterion with different calibration methods in regard of the experimental results were estimated. It could be seen that the calibrated L-H fracture criterion via both calibration methods could be qualified for the evaluation of damage evolution in the experiments under monotonic loading conditions. The addition of pre-torsion on the tension test could shift the fracture initiation point from the center to the outside edge. While for the cases under compression-torsion loading conditions, the situation is not consistent due to the cut-off value of stress traxiality used in L-H fracture criterion. With the increase of the pre-loading amount, the prediction accuracy of the identified fracture criterion deteriorates, which is probably caused by the adoption of invariant model parameters or the error of numerical simulation of strain hardening response based on the assumption of isotropic hardening.

1. Introduction

From microscopic viewpoints, ductile fracture is the integral manifestation of nucleation, growth and coalescence of voids. While from macroscopic viewpoints, with the increase of stress triaxiality from negative to positive, the mechanisms of ductile fracture are generally classified into three types: shear dominated ductile fracture, mixture of shear and tension dominated ductile fracture and tension dominated ductile fracture.

For the purpose of predicting the onset of ductile fracture, various damage models have been proposed. Considering damage accumulation induced by nucleation, growth and coalescence of voids, Gurson, Tvergaard and Needleman developed a damage model named as GTN model, taking account of the effect of damage on the plastic flow, to describe both plasticity and ductile fracture of porous materials. Due to the assumption the void growth was suppressed in negative stress triaxiality, the original Gurson model could not work well at low or negative stress triaxiality situations such as uniaxial compression.

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Nomenclature

$\sigma_1, \sigma_2, \sigma_3$	principal stress, $\sigma_1 \geqslant \sigma_2 \geqslant \sigma_3$
$\varepsilon_p, \bar{\varepsilon}_f$	plastic strain and equivalent plastic strain to fracture
σ_m	mean or hydrostatic stress, $\sigma_m = (\sigma_1 + \sigma_2 + \sigma_3)/3$
$\bar{\sigma}, \sigma$	von Mises equivalent stress and normal stress
τ_{max}	maximum shear stress
η	stress triaxiality, $\eta = \frac{\sigma_m}{\bar{\sigma}}$
L	Lode parameter
C_1, C_2, C_3	material constants in L-H ductile fracture criterion
ξ	average approximation degree

Thus abundant modifications were proposed by incorporating shear effect or damage growth for shear-dominated stress state [22,15,16].

Compared with the complicated coupled GTN family damage models, simple uncoupled ductile fracture criteria are preferred for industrial applications because of their simplicity and less constants to be calibrated. These simple models were developed based on experimental observations, analytical studies, numerical results or their combinations. Cockcroft and Latham [5] proposed a model weighted by the maximum principle stress based on the observation that ductile fracture tends to take place in the region of the maximum tensile stress. Rice and Tracey [18] approximated the growth of a single spherical void by an exponential function of the stress triaxiality. This approximation simplified the analytical results and made the Rice–Tracey model preferable to the complicated GTN family models for engineers. Brozzo et al. [3] coupled the effect of the mean stress on ductile fracture into the Cockcroft–Latham criterion. Oh et al. [17] normalized the largest principal stress in the Cockcroft–Latham criterion to provide accurate predictability in extrusion of Al 2024-T351 and in drawing of SAE 1144 cold-drawn steel. Lou and Huh [11] proposed a macroscopic ductile fracture criterion (L-H) to describe ductile fracture behavior of metals regarding nucleation, growth and shear coalescence of voids, which is assumed to be more preferable in low and medium stress triaxiality. Besides, there are lots of criteria with various forms, interesting readers could refer to the publications [21,9]

However, the proposal and validation of these ductile fracture criteria were mainly performed with simple tests like tension, compression and shear tests etc., of which the loading condition is generally monotonic. Rare attention was attached to the study of ductile fracture under non-proportional loading conditions, which is the normal state in the industry. To investigate the mixed-mode ductile fracture for biaxial tension plates containing a central crack of varying inclination angles under non-proportional loading, Chow and Lu [4] proposed a damage-coupled elastic-plastic model which is suitable for ductile fracture characterization under both proportional and non-proportional loading conditions. Compared with the fracture toughness of the pre-strained material and the virgin material, Cosham et al. [6] proposed a simple theoretical model for predicting the effect of tensile pre-strain on fracture toughness using local approach. Bao and Treitler [1] carried out a study on crack formation of notched bar under compression-tension reverse loading both experimentally and numerically. In order to predict crack formation under complex reverse loading, a new fracture model adequately taking into account the effect of pre-compression on crack formation was proposed.

According to the above-mentioned work related to the cases under non-proportional loading conditions, generally specific damage models were proposed to investigate the damage evolution during the forming process. The application of the existing ductile fracture criteria into the non-proportional loading conditions is still unclear. Thus in the current work the main objective is to evaluate the effectiveness of a selected ductile fracture criterion in the prediction of fracture initiation under a kind of non-proportional loading conditions involving shear-dominated damage as well as tension-dominated damage. The whole paper is structured as follows. Experiments under monotonic and non-proportional loading conditions were introduced in Section 2. Meanwhile the fracture related state variables were estimated based on the virtual simulations of the corresponding experiments. Section 3 addresses two kinds of calibration methods for a selected ductile fracture criterion, and presents the comparison of prediction accuracy under the monotonic loading circumstances. The feasibility of the calibrated ductile fracture criterion in the non-proportional loading conditions was investigated in Section 4 by comparing the numerical predicted load-stroke curves, fracture strokes, damage accumulation and equivalent plastic strain to fracture with the ones from the experiments. Finally, the conclusions are outlined.

2. Experiments and fracture parameters estimation

Two kinds of experiments were designed and carried out in the current work, of which one is the experiments under monotonic loading conditions and the other is the experiments under non-proportional loading conditions. All the specimens were longitudinally cut along the rolling direction from the same Al2024-T351 plate with the dimension of

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