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A comparative study of three groups of ductile fracture loci in the 3D space

Yuanli Bai [a,*], Tomasz Wierzbicki [b]

[a] Department of Mechanical and Aerospace Engineering, University of Central Florida, Orlando, FL 32816, United States
[b] Department of Mechanical Engineering, Massachusetts Institute of Technology, Cambridge, MA 02139, United States

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ABSTRACT

Ductile fracture is inherently a three-dimensional phenomenon and should be represented in the 3-D space. Sixteen fracture models are evaluated and divided into three groups: physics based models, phenomenological models and empirical models. These models are then calibrated from the three sets of experimental data, TRIP 690 and TRIP 780 steel sheets and 2024-T351 aluminum alloy. Under the assumption of monotonic loading conditions, major qualitative differences emerged from the comparison of the models in terms of the range of applicability as well as shapes of the 3D fracture envelope are discussed. Several implicit features of these models are revealed.

1. Introduction

This paper reports a comparative study on some ductile fracture models in crack-free bodies, which are different from pre-cracked elastic–plastic fracture models based on crack tip mechanics (for examples, [23,33,60]). This topic has become important and gained a lot of attention in recent years since more and more materials with high strength and/or lightweight but less ductility have entered industrial applications. Examples of such materials are advanced high strength steels [1], aluminum alloys, magnesium alloys, polymer matrix composites, and so on. These materials postulate great challenges to the prediction of fracture in manufacturing, forming process, and during service because of less ductility.

Many ductile fracture models have been proposed and extensively investigated in the mechanics community in the past decades. Studies on the micro void based ductile fracture mechanisms are usually attributed to the works by McClintock [53], Rice and Tracey [61]. This part of work had been further carried on by Gurson [26,25] and later Needleman and Tvergaard [57] as a branch of micromechanics. Hancock and Mackenzie [28], Hancock and Brown [27] verified the theories of micro void growth using experiments on notched round bars. Johnson and Cook [34] proposed an empirical model based on these findings and incorporated the effects of strain rate and temperature. Different from Johnson and Cook's model, Wilkins et al. [73] postulated a model with both pressure and stress ratio effects. The effect of stress triaxiality on fracture was put in the framework of continuum damage mechanics by Lemaitre [43] considering the thermodynamics. Instead of using stress triaxiality, Cockcroft and Latham [16] developed a model using the maximum principal stress for predicting cracks during forging of bulk metals, which was further developed by Oh et al. [59].

* Corresponding author.
E-mail addresses: bai@ucf.edu (Y. Bai), wierz@mit.edu (T. Wierzbicki).

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Nomenclature

$c_\circ, c_1, c_2, c_3, c_4, \ldots$	coefficients in different fracture models
$\sigma_1, \sigma_2, \sigma_3$	three principal stresses
s_1, s_2, s_3	three principal stresses of deviatoric stress tensor
σ_m	mean stress
$\bar{\sigma}$	equivalent stress
σ_Y	equivalent stress to yield in Gurson's model
ξ	normalized third deviatoric stress invariant
$\bar{\varepsilon}^{pl}$	equivalent plastic strain
$\bar{\varepsilon}_f$	equivalent plastic strain to fracture
D_c	critical damage indicator to in different models
A	material power strain hardening coefficient, or parameter in Wilkins' fracture model
n	material power strain hardening exponent
N	number of data points/tests
$c_\theta^{AX}, c_\theta^t, c_\theta^s, c_\theta^c$	parameters in plasticity model by Bai and Wierzibicki
$d_\circ, d_1, d_2, d_3$	different coefficients in Crash-EM fracture model
η	stress triaxiality
η_1, η_2	stress triaxiality parameter in Gurson model by Nielsen and Tvergaard
$\eta_{cut-off}$	cut-off value of stress triaxiality below which fracture never occurs
L	Lode parameter
χ	Lode parameter used in Xue's model
$\bar{\theta}$	Lode angle parameter (normalized Lode angle)
τ_s	maximum shear stress to fracture
$\tau_{\max}$	maximum shear stress
k_s	fracture model parameter in Crash-FEM model
k_w	fracture model parameter in fracture model by Nahshon and Hutchinson
λ	fracture parameter in Wilkins' model, or plastic strain amplifier in Gurson's model
μ	fracture parameter in Wilkins' model
m	fracture parameter in Xue-Wierzbicki's model
f	fracture model parameter in Crash-FEM model, or volume fraction of micro void in Gurson type models
$f_\circ, f_f, f_c$	initial or critical volume fractions of micro void in Gurson type models
$\dot{f}_{growth}, \dot{f}_{nucleation}, \dot{f}_{shear}$	changing rate of volume fractions of micro void in Gurson type models
q_1, q_2, s_N, f_N, f^*	different coefficients in Gurson type models
ϕ	plastic potential function in Gurson type models
F_{zb}^f	fracture parameter in McClintock's model

These parts of work were revisited by Bao [7], Bao and Wierzbicki [9] using carefully designed fracture tests together with finite element simulation. Fracture mechanisms of metallic materials were divided into three modes: "ductile fracture", "shear fracture" and mixed mode [9,31]. It was found that the ductile fracture strain is not necessary a monotonic decreasing function of stress triaxiality in general. This finding was further developed by Wierzbicki and Xue [71], Xue [74], Bai and Wierzbicki [5] to incorporate the effect of Lode angle (related to the third deviatroic stress invariant J_3) to ductile fracture. It was shown by Bai and Wierzbicki [6] that these two crack modes and their interaction can be interpreted by the classical Mohr–Coulomb [17,55] fracture model, which considers combined effects of normal stress and shear stress. Experimental results on advanced high strength steels validated the applicability of the modified Mohr–Coulomb model [50,45]. Gao et al. [21] showed strong effects of both pressure and the Lode angle on plasticity and ductile fracture of aluminum 5083 alloy. Lian et al. [46] demonstrated both pressure and Lode angle dependency on ductile fracture of dual-phase steel. Instead of using Lode angle (parameter) but Lode parameter, Lou et al. [48], Lou and Huh [47] proposed a criterion by directly incorporating the existence of cut-off value of stress triaxiality. Khan and Liu [39] proposed an isotropic fracture criterion based on the magnitude of stress vector (MSV), which has been recently extended to study the effect of strain rate and temperature [38]. Voyiadjis et al. [69] studied the ductile fracture use three stress invariants directly and considered the effect of reverse loading.

Introducing the effect of Lode angle was also done for Gurson type micro void based models. Nahshon and Hutchinson [56] and Nielsen and Tvergaard [58] considered the effects of micro void shear by introducing a new term in the evolution equation of micro void volume fraction. Xue [75] took this effect into account by incorporating a shear damage term. Malcher et al. [52] extended the Gurson type model to consider the void shear mechanism and damage effect. Dunand and Mohr [19] compared the prediction of shear modified Gurson models with the modified Mohr–Coulomb model using test data of TRIP-assisted steel sheets. Li et al. [44] evaluated several damage uncoupled/coupled ductile fracture criteria and Gurson–Tvergaard–Needleman (GTN) model using comprehensive test data on Al 6061-T6 alloy. The combining effects of stress