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Calibration of ductile fracture criteria at negative stress triaxiality

Petr Kubík [a], František Šebek [a,*], Jiří Hůlka [b], Jindřich Petruška [a]

[a] Institute of Solid Mechanics, Mechatronics and Biomechanics, Faculty of Mechanical Engineering, Brno University of Technology, Technická 2896/2, 616 69 Brno, Czech Republic
[b] Institute of Applied Mechanics, Resslova 972/3, 602 00 Brno, Czech Republic

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ABSTRACT

The aluminium alloy 2024-T351 and AISI 1045 carbon steel was examined in scope of uncoupled ductile fracture criteria calibration using newly designed specimen. Its novel geometry allowed to reach extremely low stress triaxialities. The analysis of fracture envelopes was carried out with comparison of each criteria cut-off regions after the calibration where one novel criterion, KHPS, has been introduced. Ductile fracture criteria implemented into the commercial finite element code Abaqus through user subroutine VUMAT were applied to simulation of compression of newly designed cylinder with specific recess to show the crack prediction ability using the element deletion technique. Crack initiation loci together with force responses were compared to experimental observations.

1. Introduction

Uncoupled ductile fracture criteria has been used for failure prediction under large inelastic deformations in various applications. There are many models based on different approaches in literature which might be classified in two basic categories, coupled and uncoupled. Coupled models have the damage associated with plasticity. The level of damage is estimated on the basis of loading history and stress–strain relationship which consequentially degrades as the damage increases. Damage is obtained in the same way in case of uncoupled models but the plasticity is not influenced.

One of coupled ductile fracture approaches is continuum damage mechanics. Kachanov [1] assumed the weakening factor related to highest tensile stress. On this basis, Rabotnov [2] introduced the damage parameter related to the weakening factor expressing the loss of load carrying area. Lemaitre [3] proposed the continuum damage model with damage parameter related to the equivalent plastic strain. Later, Bonora [4] presented isotropic non-linear model capable to describe damage accumulation for various materials. Recently, another damage mechanics approach was proposed by Xue [5].

Another widespread group of coupled criteria are porosity based models. These do not calculate the damage separately from the plasticity but include the void volume fraction as internal variable which is correlated to damage of material. There have been many modifications of model proposed by Gurson [6]. Tvergaard [7] and Tvergaard and Needleman [8] considered more than one void and the model proposed by Gurson extended by two another constants on the experimental basis to improve the prediction ability shortly before the failure. This model is also known as GTN after authors. Xue [9] or Malcher et al. [10] presented modification introducing the void shear linkage under low stress triaxiality loadings.

One of microscopically based approaches is the one based on the void nucleation, growth, and coalescence introduced by McClintock [11] who analytically studied the growth of cylindrical voids placed in plastic material. Results revealed strong dependence of fracture strain on the stress triaxiality. Rice and Tracey [12] investigated the growth of one spherical void in an infinite solid subjected to a remote stress field and confirmed results of, among others, Bridgman [13] that the plastic deformation at fracture is strongly dependent on the stress triaxiality. LeRoy et al. [14] modified criterion proposed by Rice and Tracey by allowing the change of void shape. Nowadays, the microstructure of ductile fracture might be experimentally analysed through the microtomography [15]. Apart from the nucleation, growth, and coalescence mechanism, there have later been proposed criteria including the shear mechanism which plays the role at low and negative stress triaxiality regimes [16]. Criteria proposed by Wilkins et al. [17] or CrashFEM [18] were developed in the

* Corresponding author. Tel.: +420 54114 4925.
E-mail address: sebek@fme.vutbr.cz (F. Šebek).

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cooperation with automotive industry to be applied to thin sheets and extrusions under the plane stress condition.

Many of older uncoupled or phenomenological models have been introduced in order to apply them to various manufacturing processes, such as extrusion, drawing, or rolling [19–21]. These criteria are rather empirical and very simple. In the last decade, these models were followed up by sophisticated criteria incorporating also the deviatoric stress state parameter apart from the stress triaxiality [22–24]. Application of these criteria is universal because of covering all types of stress states. In this spirit, there was proposed one novel uncoupled ductile fracture model, KHPS, in the present paper.

Calibration of uncoupled models is carried out using various fracture tests to cover a broad range of stress states and to provide reliable and universal fracture models. Moreover, model proposed by Xue and Wierzbicki [25] and Extended Mohr–Coulomb criterion [26] contain constants related to plasticity apart from fracture related material constants. Plasticity related constants are necessary to estimate before the fracture criteria calibration. Tensile tests of smooth and notched cylindrical specimens belong to basic tests [27,28]. These map wide range of stress triaxiality under the axisymmetric tension when the material shows increased ductility. Wierzbicki et al. [25] carried out 15 fracture tests on aluminium alloy 2024-T351 in the range of stress triaxiality approximately from −0.3 to 1.0 together with calibration of seven uncoupled models. Li et al. [29] designed a group of specimens for a wide range of stress states and deformation modes as well and using these specimens identified material constants of two coupled criteria, GTN and Lemaitre-based model, for aluminium alloy 6061-T6. Wierzbicki et al. [22] presented universal specimen, the so-called butterfly specimen, capable of reaching different stress states by changing the combination of tension or compression and shear loading. Mohr and Henn [30] have proposed different shape of a butterfly specimen which Dunand and Mohr [31] later optimised. Another universal calibration specimen is the one with double-notched tube geometry designed for applying tension and torsion loading combinations [32,33]. Very high stress triaxialities can be reached with this specimen under the dominant tension due to small notch radii. Apart from this specimen, Graham et al. [34] also used another alternation of the geometry proposed by Gao et al. [35].

Four uncoupled fracture models for aluminium alloy 2024-T351 and carbon steel AISI 1045 have been calibrated, including newly designed cylindrical specimen. This cylinder with specific recess is capable to reach extremely low stress triaxiality. There was conducted the analysis of fracture envelopes and fracture strains for all tests after the calibration process. Khan and Liu [36] carried out an analysis of selected criteria for aluminium alloy 2024-T351 on the basis of fracture stress. Lou et al. [37] proposed a criterion with a changeable cut-off value and applied it to aluminium alloy 2024-T351 as well. Then, the error analysis was carried out on the basis of both the fracture strain and fracture stress. It is more reasonable and suitable to use the strain error analysis in the light of stress and strain resolution regarding the ductile fracture (Fig. 1).

The region with no fracture, the so-called cut-off value, in scope of ductile fracture was discussed by Bao and Wierzbicki [38] on the basis of compression tests and analysis of comprehensive work of Bridgman [13] to reveal that the fracture does not occur under the stress triaxiality less than −0.3. Teng and Wierzbicki [39] confirmed the importance of the region without fracture occurrence in simulations of different types of projectiles which impacted into aluminium and steel sheets. Khan and Liu [36] carried out a non-proportional biaxial compression test of aluminium alloy 2024-T351 in the channel fixture when the fracture occurred along maximum shear direction. In this case, the stress triaxiality reached almost −0.5. Tutyshkin et al. [40] conducted compression tests of cylinders with ratio of the initial diameter to the initial height 0.75, 1.00, and 1.25. Specimens from copper, steel, and aluminium–magnesium alloy had variously horizontally and vertically placed cylindrical holes. The strains 1.04–1.67 were obtained at stress triaxiality from −1/3 to −2/3 in these experiments. Novel specimen presented in this paper reached the average value of stress triaxiality lower than −1/3 in the locus of crack initiation. This specimen was used for calibration of 3 uncoupled ductile fracture criteria together with 1 newly proposed one for aluminium alloy 2024-T351 and carbon steel AISI 1045.

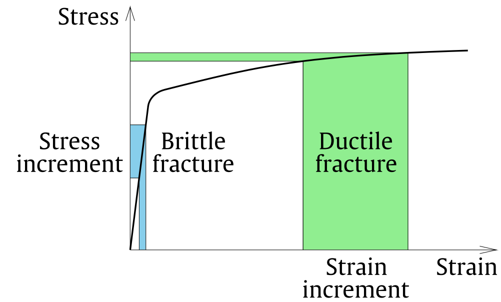

Fig. 1. Stress and strain increments regarding the ductile fracture [26].

2. Selected and proposed uncoupled ductile fracture criteria

In the following chapter, 3 fracture criteria were selected and 1 novel was proposed. All 4 aforementioned uncoupled criteria include the cut-off value. For the following criteria, rate of damage accumulation is constant and expressed by

$$D = \int_0^{\bar{\varepsilon}_D} \frac{1}{\bar{\varepsilon}_f} \, d\bar{\varepsilon}_p, \tag{1}$$

where the $\bar{\varepsilon}_D$ is the cumulative plastic strain for a given loading path, $\bar{\varepsilon}_f$ is the fracture strain (usually dependent on other field variables as stated further), and $\bar{\varepsilon}_p$ is the equivalent plastic strain. The fracture occurs when the damage parameter reaches the unity.

As a field variable describing the dimensionless mean stress might be used the stress triaxiality

$$\eta = \frac{\sigma_m}{\bar{\sigma}}, \tag{2}$$

where σ_m is the mean stress and $\bar{\sigma}$ is the equivalent von Mises stress. Variable describing the effect of deviatoric stress tensor $\mathbf{S}$ might be the normalised third invariant of deviatoric stress tensor

$$\xi = \frac{27}{2} \frac{\det(\mathbf{S})}{\bar{\sigma}^3}, \tag{3}$$

or the normalised Lode angle

$$\bar{\theta} = 1 - \frac{2}{\pi} \arccos(\xi), \tag{4}$$

and the Lode parameter

$$\mu = \sqrt{3} \tan\left(-\frac{\pi}{6}\bar{\theta}\right). \tag{5}$$

Averages of state variables were used in the calibration process. Those were calculated as

$$\eta_{av} = \frac{1}{\hat{\varepsilon}_f} \int_0^{\hat{\varepsilon}_f} \eta \, d\bar{\varepsilon}_p, \tag{6}$$