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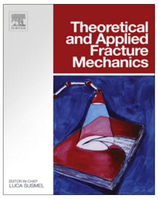

Analysis of fracture criteria for 7050 aluminum alloy with different geometries based on the elastic strain energy density

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ABSTRACT

A fracture criterion based on the elastic strain energy density (ESED) is used in consideration of the effect of structural geometry and mechanical properties, including the ultimate tensile strength, stress intensity factor, stress concentration factor and specific surface energy. A normalized damage variable D_N is defined to represent the ductile damage within the plastic deformation zone. To investigate the fracture behavior using the energy fracture criterion, structural parts of different geometries are studied by testing 7050-T7451 aluminum alloy standard specimens: standard tensile specimen, hole specimen and compact tension specimen. Finite element models are established for each specimen, and the corresponding experimental processes are simulated. The numerical results are consistent with the experimental results. By comparing and analyzing the results, the effects of different geometries on the deformation damage and fracture process, the energy condition of crack propagation, fracture orientation and fracture morphology are discussed.

1. Introduction

It is well-known that damage occurs and constantly evolves into fracture when the damage accumulates to a certain limit in the plastic deformation zone. The process of void nucleation, growth and coalescence plays an important role on the crack growth and fracture of metal materials [1,2]. The initial damage theory was first established based on the continuum damage mechanics (CDM) theory; then, further studies were developed in microscopic damage mechanisms [3,4]. Due to the complexity of the material microstructures, there are few models able to fully describe the entire process of mesoscopic damage and ductile fracture, and only the corresponding damage phenomenon can be explained. Das et al. [5] observed that strain-induced damage accumulations occurs in a manner, that is very sensitive to the stress state also using void growth data. Gilioli et al. [6] employed a ductile damage criterion to predict the damage behavior of Al6061-T6 compact specimens in fracture toughness tests and discussed the effect of localized phenomena. Jackiewicz [7] calibrated material parameters and evaluated the probability of structural failure based on the combined fracture model of micro-void growth. Tasan et al. [8] presented an in-depth comparison of six theoretically equivalent damage quantification methodologies to determine material-specific damage parameters for CDM.

Recently, various fracture criteria have been proposed and applied to describe the deformation process under various loading conditions. Selecting a reasonable fracture criterion to predict ductile fracture with different fracture mechanisms can help the industry to realize better design and optimization of products and processes [9]. Abbassi et al. [10] analyzed the fracture and instability in necking processes during simple and complex load testing by addressing the effect of ductile damage evolution. Xue et al. [11] proposed a ductile–brittle fracture criterion based on a micro-void mechanical model for micro-damage and fracture of a metallic material subjected to large elastic–plastic deformation. Lou et al. [12] proposed a macroscopic ductile fracture criterion based on the micro-mechanism analysis of nucleation, growth and shear coalescence of voids from the experimental observation of fracture surfaces. Xue et al. [13] presented a ductile fracture criterion based on the Gurson model [14] that depends on stress triaxiality and the second stress invariant. Ma et al. [15] presented a normalized ductile damage criterion based on strain hardening exponent, stress triaxiality and strain Lode parameters to analyze forming limit in sheet metal hydraulic bulging test.

A widely accepted strain energy density (SED) criterion was proposed by Sih [16]. The SED criterion as a powerful tool predicts well the ductile and brittle fracture behavior of cracked and notched components and works well in many applications. Many researchers have extended different SED-based approaches. Taghizadeh et al. [17] assessed the static strength of U-notched

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specimens under mixed mode loading based on the averaged SED criterion. Lazzarin and Zambardi [18] used finite-volume-energy based approach to be able to accurately predict both the static and fatigue behavior of severely notched components, and then discussed the link between local SED and notch stress intensity factors and observed that the SED-based procedure is useful to determine rapidly theoretical stress concentration factors for holes and blunt U- and V-shaped notches [19], recently, compared the energy- and stress-based fracture criterion about V-notched components by means of notch stress intensity factors (NSIFs) [20]. Berto and Lazzarin [21] summarized the volume-based strain energy density approach applied to V-notches and welded structures. Recently, Berto and Lazzarin [22] investigated the multiaxial fatigue behavior of Ti–6Al–4V by using severely notched structural components under pure tension and pure torsion loading and different nominal load ratios, and the approach based on the SED averaged on a control volume embracing the highly stressed region is employed to summarize all the data in a single scatter band. Wei [23] extended the SED criterion for crack kinks and material failure by weighting the volumetric and the distortional parts differently. Lazzarin discussed the link between local SED and notch stress intensity factors and observed the SED-based procedure is useful to determine theoretical stress concentration factors for holes and blunt U- and V-shaped notches. The initiation of macroscopic material failure is associated with the collective disruption of atomic bonds, which is driven by the release of potential elastic strain energy. In this work, an elastic strain energy density (ESED) function related to stress triaxiality is used to analyze the material damage and fracture process considering the effect of mechanical properties and structural geometry. Hence, stress triaxiality is related to material damage and fracture process, and it is used to be taken into the establishing of ductile–brittle criterion. According to the effect of parameters such as the material ultimate strength, stress intensity factor, critical strain energy density factor, stress concentration factor and specific surface energy on deformation damage and fracture behavior, a ductile–brittle fracture criterion is used.

The deformation damage and fracture of structural components for aviation are the basis of damage tolerance and whole-life design. 7050 aluminum alloy exhibited a good combination between the strength and fracture toughness compared to the conventional aluminum alloys such as 2xxx series and Al–Li alloys [24]. 7050-T7451 aluminum alloy is a super-high strength alloy, and its yield strength approaches tensile strength. In addition, its weight is light, so it is widely used in aerospace and automotive industries [25,26]. But the failure usually occurs in practical applications, which limits its wide applications. Thus, 7050-T7451 aluminum alloy is studied in this paper to investigate the fracture behavior.

In this work, to investigate the fracture behavior using the fracture criterion based on ESED and damage evolution, structural parts of different geometries are studied by testing 7050-T7451 aluminum alloy standard specimens: standard tensile specimen, hole specimen and compact tension specimen. Finite element models are established for each specimen, and the corresponding experimental processes are simulated.

2. Damage and fracture

2.1. Damage characterization

Due to the formation of micro-voids and micro-cracks introduced in the material by deformation in material, the apparent elastic modulus gradually decreases. According to [27] the apparent elastic modulus can be described as:

$$E_D = E_0 e^{-p\varepsilon_p} \tag{1}$$

where E_0 is the initial elastic modulus ($\varepsilon_p = 0$), p is a constant related to the material which is obtained by interrupted uniaxial tension test, where $p = \frac{9}{4}(1-\nu)$ [27] (in the non-uniform deformation stage), $p = 1$ (in the uniform deformation stage), E_D is the apparent elastic modulus of the damaged material, and its corresponding plastic strain is ε_p.

The damage variable D can be expressed by the elastic modulus:

$$D = 1 - \frac{E_D}{E_0} = 1 - e^{-p\varepsilon_p} \tag{2}$$

Considering the different loading conditions, stress-state parameters and deformation pattern, the ductile damage degree and the plastic fracture behavior can be characterized by a normalized damage variable D_N:

$$D_N = \frac{D_i}{D_C} \tag{3}$$

where D_i is the accumulated damage value in the plastic deformation process, D_c is the critical value of ductile damage in the uniaxial tensile stress state (stress triaxiality $R_d = 1/3$ and strain Lode parameter $\mu_\varepsilon = -1$), which can be obtained by

$$D_c = f(R_d, \mu_\varepsilon)(1 - e^{-p\varepsilon_f}) \tag{4}$$

where ε_f is the true fracture strain, $f(R_d, \mu_\varepsilon)$ is a function of stress-state parameters (R_d and μ_ε), which can be expressed as [11]:

$$f(R_d, \mu_\varepsilon) = (0.279 - 0.004\mu_\varepsilon)e^{1.5R_d} - (0.279 + 0.004\mu_\varepsilon)e^{-1.5R_d} \tag{5}$$

The stress triaxiality $R_d = \sigma_m/\sigma_{eq}$ reflects the stress-state complexity, i.e., the stress state is inclined to be tensile when $R_d > 0$, while the stress state tends to be compressive when $R_d < 0$, and the stress state is pure shear when $R_d = 0$ [28]. The equivalent von Mises stress σ_{eq} and hydrostatic stress σ_m defined as in Eqs. (6) and (7), respectively:

$$\sigma_{eq} = \sqrt{[(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_1 - \sigma_3)^2]/2} \tag{6}$$

$$\sigma_m = (\sigma_1 + \sigma_2 + \sigma_3)/3 \tag{7}$$

where $\sigma_1 \geqslant \sigma_2 \geqslant \sigma_3$ are the three principal stress.

The Lode parameter $\mu_\varepsilon = 2((\dot{\varepsilon}_2 - \dot{\varepsilon}_3)/(\dot{\varepsilon}_1 - \dot{\varepsilon}_3))$ reflects the strain–states complexity, i.e., the strain state is inclined to be tensile when $\mu_\varepsilon < 0$; the strain state tends to be compressive when $\mu_\varepsilon > 0$; the strain state is pure shear when $\mu_\varepsilon = 0$ [29]. $\dot{\varepsilon}_1 > \dot{\varepsilon}_2 > \dot{\varepsilon}_3$ are the principal strain rate in the remote strain field.

To calculate the accumulation of deformation damage in the loading path, the incremental form can be adopted:

$$\Delta D_i = f_i(R_d, \mu_\varepsilon) p e^{-p\varepsilon_i} \Delta\varepsilon_i, \quad i = 1, 2, \ldots, k \tag{8}$$

where k is the number of load steps. The accumulation of damage in the plastic deformation process can be represented as:

$$D_i = D_{i-1} + \Delta D_{i-1} \tag{9}$$

When $D_i \leqslant 0$, the value of Eq. (7) is supposed to be zero. Combined with Eqs. (4) and (9) can be used to calculate the damage variable D_N accumulated within the material plastic deformation zone. If the damage variable D_N is close to 0, it indicates that the material is undamaged or damage repaired (materials can be welded together under compressive state). If D_N is close to 1, the material tends to the limit deformation damage and reaches ductile fracture.

2.2. Fracture criterion

A structural component exhibits material properties and geometrical characteristics, and is a combination which included the