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Experimental and numerical investigation for ductile fracture of Al-alloy 5052 using modified Rousselier model

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ABSTRACT

In this paper, the ductile fracture of Al-alloy 5052 is studied by experiments and simulations using a modified Rousselier model. Although tension failure has been successfully predicted by the classical Rousselier model, its predictive capability on shear failure was seldom discussed. A modified Rousselier model was proposed by incorporating the recent extended damage evolution model by Nahshon and Hutchinson. The modified Rousselier model can capture both tension and shear failure. A stress integration algorithm based on the general backward-Euler return algorithm for this constitutive model was developed and implemented into finite element model by the user defined material subroutine VUMAT in the ABAQUS/Explicit. The tensile tests of smooth round bar and notched round bars with different sizes were carried out to investigate the mechanical behavior of Al-alloy 5052. Consequently, the material parameters of the classical Rousselier model were identified by an inverse method using these experimental data. A shear test was also performed to calibrate the new shear damage coefficient in the modified Rousselier model. For the shear test, the simulations show that although shear failure can be predicted by the Rousselier model, the ductility was over-estimated. However, the modified Rousselier model can give more accurate results. The simulations on uniaxial tension of the round bars also confirm that the modified Rousselier model can well predict the cup-cone fracture mode. The results indicate that the Lode parameter in the new damage evolution model is important to capture the cup-cone fracture mode transition.

1. Introduction

It is well known that when metal fractures, microvoids will experience a complex process, including the nucleation, growth and coalescence. In order to describe this damage and fracture process, many ductile fracture models using local approaches have been published. In the view of macroscopic phenomenology, the Gurson model in [1] developed well in the past decades. The calibration methods for Gurson model were proposed [2,3] and it was widely used in the prediction of ductile fracture in [4–6].

The mean stress $\sigma_m = \sigma_{kk}/3$ and effective stress $\sigma_{eq} = (3\underline{\sigma}_d : \underline{\sigma}_d/2)^{1/2}$ play important roles in ductile fracture [1], but the relation between the effective plastic strain at fracture and the stress triaxiality ($\eta = \sigma_m/\sigma_{eq}$) is not generally monotonic [7,8]. Also, some experiments in [9] show that the ductility and fracture mechanism of metals is also influenced by the Lode parameter. More and more tests show that the damage in material is influenced by shear deformation as well as tension [10,11]. But the void evolution function used in Gurson's model showed limitations in recent years for its inapplicability to localization and fracture for low triaxiality or shear-dominated deformations [12]. So, a non-dimensional metric of stress $\omega(\underline{\sigma})$ was recommended to discriminate between axisymmetric and shear-dominated stress states in [12]. And then an extension of the damage growth function was proposed which incorporates damage growth under low triaxiality such as shear-dominated state [12]. The modified Gurson model was utilized to simulate quasi-static punch-out tests of high ductility DH36 steel in [13]. In [14], a whole calibration procedure for this model was given using a finite element (FE)-based inverse method. The predictive capability of the modified Gurson model was evaluated in [15,16] by a series of experiments and simulations. In [17], a shear void nucleation term based on the Lode parameter for plastic strain rate is used to model slant fracture by Morgeneyer and Besson. In [18], Li et al. research shows that the applicability of the ductile fracture criteria depends on the use of suitable damage evolution rules and consideration of several influential factors, including the Lode parameter, etc.

After Rousselier published his damage model based on continuum damage mechanics in [19–21], some numerical computational methods and simulations have been done in [22–32], aimed at proposing robust and reliable FE formulations and developing this model to a non-local and mesh independent model, etc. The recent research on the Rousselier model in [23] shows that the

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cup-cone fracture mode in tension test of notched round bar can be predicted. In [30,31], the Rousselier model's predictive applicability under shear deformation was mentioned but has not been assessed yet. In this paper, the capability of the Rousselier model is assessed and it is shown that some modifications on damage evolution are required.

2. Modified Rousselier model

In this section, a brief introduction of the Rousselier model is given and followed by its modification. Rousselier developed the simplest possible model of porous metal plasticity in the framework of thermodynamics of irreversible processes in [19]. The material's isotropy and elastic-plasticity with isotropic hardening are assumed in this model. Two internal variables are used to quantify the deterioration process of material, one is the equivalent plastic strain p and the other is the so-called damage variable or void volume fraction f. The Rousselier damage model includes yield potential, stress strain relation, normality rule, and the evolution of damage variable. The yield potential is written as Eq. (1), so it is a coupled constitutive equation in which the damage accumulation and hydrostatic stress are incorporated.

$$\Phi = \frac{\sigma_{\mathrm{eq}}}{\rho} - R(p) + Df\sigma_1 \exp\left(\frac{\sigma_m}{\rho\sigma_1}\right) = 0 \tag{1}$$

where $\underline{\underline{\sigma}} = \underline{\underline{\sigma}}_d + \sigma_m \underline{\underline{I}}$ is the Cauchy stress tensor, $\underline{\underline{\sigma}}_d$ is the deviatoric tress tensor, σ_m is hydrostatic stress, $\underline{\underline{I}}$ is the second order unity tensor, $\sigma_{eq} = (3\underline{\underline{\sigma}}_d : \underline{\underline{\sigma}}_d/2)^{1/2}$ is the von Mises equivalent stress, $\rho = (1-f)/(1-f_0)$ is the relative density, f is the damage variable or void volume fraction, f_0 is the initial void volume fraction in the material, $R(p)$ is the hardening function of the material, $p = (2\underline{\underline{\varepsilon}}_d^p : \underline{\underline{\varepsilon}}_d^p/3)^{1/2}$ is the equivalent plastic strain, D and σ_1 are Rousselier material constants, usually $D = 2$ [18–20]. The stress strain relation or Hooke's Law is written as the following equation:

$$\underline{\underline{\sigma}} = \rho \underline{\underline{\underline{\underline{E}}}} : \underline{\underline{\varepsilon}}^e = \rho \underline{\underline{\underline{\underline{E}}}} : (\underline{\underline{\varepsilon}} - \underline{\underline{\varepsilon}}^p) \tag{2}$$

where $\underline{\underline{\underline{\underline{E}}}}$ is the elastic modulus tensor, $\underline{\underline{\varepsilon}}$ is the strain tensor, $\underline{\underline{\varepsilon}}^e$ and $\underline{\underline{\varepsilon}}^p$ are the elastic and plastic part of strain tensor respectively. Using the normality rule, the plastic strain rate tensor can be expressed as Eq. (3).

$$\dot{\underline{\underline{\varepsilon}}}^p = \dot{p}\frac{\partial\Phi}{\partial(\underline{\underline{\sigma}}/\rho)} = \dot{p}\left[\frac{3\underline{\underline{\sigma}}_d}{2\sigma_{eq}} + \frac{1}{3}Df\exp\left(\frac{\sigma_m}{\rho\sigma_1}\right)\underline{\underline{I}}\right] \tag{3}$$

It is remarkable that the plastic part of strain tensor can be divided into the deviatoric part and volumetric part by $\underline{\underline{\varepsilon}}^p = \underline{\underline{\varepsilon}}_d^p + \varepsilon_m^p \underline{\underline{I}}$, therefore, the deviatoric part of plastic strain rate tensor can be given as:

$$\dot{\underline{\underline{\varepsilon}}}_d^p = \dot{p}\frac{3\underline{\underline{\sigma}}_d}{2\sigma_{eq}} \tag{4}$$

And the volumetric plastic strain rate was derived as the following equation:

$$\dot{\varepsilon}_m^p = \frac{1}{3}\dot{p}Df\exp\left(\frac{\sigma_m}{\rho\sigma_1}\right) \tag{5}$$

The relation between the damage variable with the volumetric plastic strain rate used in Rousselier model was derived by mass conservation as the following equation:

$$\dot{f} = 3(1-f)\dot{\varepsilon}_m^p \tag{6}$$

By substituting Eq. (5) into Eq. (6), the evolution rate of the damage variable can be written as a function of the equivalent plastic strain rate and mean stress:

$$\dot{f} = Df(1-f)\exp\left(\frac{\sigma_m}{\rho\sigma_1}\right)\dot{p} \tag{7}$$

According to Nahshon and Hutchinson in [12], the void growth is no longer directly tied to the plastic volume change as it is in the original model, and simply treated as a parameter measuring the damage accumulation in the material. It is recommended that the void evolution rate can be written as Eq. (8) with an additional phenomenological term. It results in a maximum effect for pure shear and no effect for axisymmetric stress states.

$$\dot{f} = 3(1-f)\dot{\varepsilon}_m^p + k_\omega f\omega(\underline{\underline{\sigma}})\frac{\underline{\underline{\sigma}}_d\dot{\underline{\underline{\varepsilon}}}_d^p}{\sigma_{eq}} \tag{8}$$

Here k_ω is the shear damage coefficient, which sets the magnitude of the void coalescence rate in shear deformation [12–16]. And the invariant measure $\omega(\underline{\underline{\sigma}})$ is given by

$$\omega(\sigma) = 1 - \xi^2 = 1 - \left(\frac{27J_3}{2\sigma_{eq}^3}\right)^2 \tag{9}$$

$$J_3 = \det(\underline{\underline{\sigma}}_d) = (\sigma_I - \sigma_m)(\sigma_{II} - \sigma_m)(\sigma_{III} - \sigma_m) \tag{10}$$

Here $\xi = \frac{27J_3}{2\sigma_{eq}^3}$ is the Lode parameter in [18], or normalized third invariant in [16] and lies in the range $-1 \leqslant \omega \leqslant 1$, J_3 is the third stress invariant of the deviatoric tress tensor $\underline{\underline{\sigma}}_d$, σ_I, σ_{II} and σ_{III} are the principal stresses of the tress tensor $\underline{\underline{\sigma}}$ and are assumed to be ordered as $\sigma_I \geqslant \sigma_{II} \geqslant \sigma_{III}$. The non-dimensional metric in Eq. (9) lies in the range $0 \leqslant \omega \leqslant 1$ to discriminate between axisymmetric and shear-dominated stress states. For all axisymmetric stress states, $\omega = 0$. And for all states comprised of a pure shear stress plus a hydrostatic contribution, $\omega = 1$ (see details in [12]). Here, the Lode angle θ could be introduced as Eq. (11), which is the same definition as in [10].

$$\cos(3\theta) = \frac{27J_3}{2\sigma_{eq}^3} \tag{11}$$

Then the relation between the non-dimensional metric $\omega(\underline{\underline{\sigma}})$ and the Lode angle could be introduced as

$$\omega(\underline{\underline{\sigma}}) = \sin^2(3\theta) \tag{12}$$

Substitute Eqs. (4) and (5) into Eq. (8), then a new damage evolution rule could be derived as the following equation:

$$\dot{f} = \left[Df(1-f)\exp\left(\frac{\sigma_m}{\rho\sigma_1}\right) + k_\omega f\omega(\underline{\underline{\sigma}})\right]\dot{p} \tag{13}$$

When elasticity is neglected, the mean stress $\sigma_m = 0$, and $\omega(\underline{\underline{\sigma}})$ keeps as constant, Eq. (13) can be transferred to an ordinary differential equation

$$\frac{df}{dp} = Df(1-f) + k_\omega\omega(\underline{\underline{\sigma}})f \tag{14}$$

With f_0 as the initial void volume fraction, the analytical solution can be derived as:

$$f = \frac{(D + k_w\omega(\underline{\underline{\sigma}}))f_0}{(D + k_w\omega(\underline{\underline{\sigma}}) - Df_0)e^{-(D+k_w\omega(\underline{\underline{\sigma}}))p} + Df_0} \tag{15}$$

Then for the shear stress state, the solution can be particularized with $D = 2$, and $\omega(\underline{\underline{\sigma}}) = 1$ as

$$f = \frac{(2 + k_w)f_0}{(2 + k_w - 2f_0)e^{-(2+k_w)p} + 2f_0} \tag{16}$$

By substituting $f_0 = 10^{-4}$ and different $k_w = 0.0, 0.5, 1.0, 1.5$ into Eq. (15), the evolution of damage variable with respect to the equivalent plastic strain p can be obtained as Fig. 1. It can be seen