Characterization of damage and toughness of 5052 aluminum alloy based on continuum damage mechanics

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Abstract. Elastic modulus was applied to estimate the damage variable based on continuum damage mechanics. A damage evolution equation was derived and the variation of damage characteristics with deformation was also discussed. Repeated loading-unloading tensile tests were conducted on 5052 aluminium alloy. It was found that the yield strength increased with the plastic stain until fracture, then the yield hardening model was established. An equivalent sine model was employed to illustrate stress-strain relationship according to the principle of double atoms model. Toughness indicator and plastic deformation energy indicator were introduced to describe the toughness feature in metals and the parameters were formulated by conventional mechanical properties of metals. It was shown that the parameters can well characterize the material toughness in deformation process and plastic energy in crack propagation.

1. Introduction

Cold deformation of metals is an important mode of plastic processing, which is widely used in various forming process of aviation and aerospace industries. Most cold working process could lead the work-hardening phenomenon and enhance the strength before structural components serve [1-3]. However, the pre-deformation brings profound influences on fracture behavior to components. With the plasticity and ductility of the forming components getting down, as well as the initial damage existed in the materials, damage such as micro-voids grow and get together until form the macro-cracks. Therefore, the prediction of crack initiation position, expansion conditions and directions, and the control of defects to avoid the fracture and failure of materials have become a research hotspot in the area [4].

Different methods have been studied by many researchers to define damage of materials. Generally, there are two kinds of damage criteria, the macro-criteria and the micro-criteria. As to macro-criteria, the damage variable can be represented by elastic modulus, density, electrical resistance, hardness, and ultrasonic etc [5-6]. In continuum damage mechanics (CDM), Kasyanov [7] firstly introduced a damage variable from 0 to 1 to characterize the deterioration of the mechanical properties in materials. As to micro-criteria, the damage can be directly measured by the micro-cracks and micro-voids [8]. The macro-physical variables, which are sensitive to material damage and are easily measured, are often adopted to define the micro-damage variable. However, the damage variables are different when different damage criteria are applied to evaluate damage for the same material. It is difficult to evaluate

the damage degree of material and predict the critical damage value at fracture point. Consequently, the unified damage function is required to describe various material damages.

5052 aluminum alloy (AA5052) is the Al-Mg antirust aluminum alloy with good corrosion resistance. The alloy has lower magnesium content, higher plasticity, well formability and inferior strength. The strength increases and plasticity decreases after cold-working. It is suit for manufacturing the weld assembly and components with good plasticity and corrosion resistance, such as fuel tanks, gasoline pipes and light-load components [9-10]. This paper investigated the damage and toughness of AA5052 based on continuum damage mechanics. Repeated loading-unloading tensile tests were conducted and yield hardening model was established. The material toughness was discussed form the view of elastic modulus and energy.

2. Experimental procedure

In this work, 5052 aluminum alloy plates were cutting along the rolling direction into the standard tensile specimens (Dog-bone shape), with thickness 1 mm. The repeated loading-unloading tests were conducted by electronic tensile test machine according to the method introduced by Lemaitre and Dufailly [11]. The prestress was 50 MPa for each specimen and the specimens were reloaded with increasing stress of 10 MPa until fracture at loading rate of 10 s^{-1}. The true stress-strain curves were shown in Fig.1.
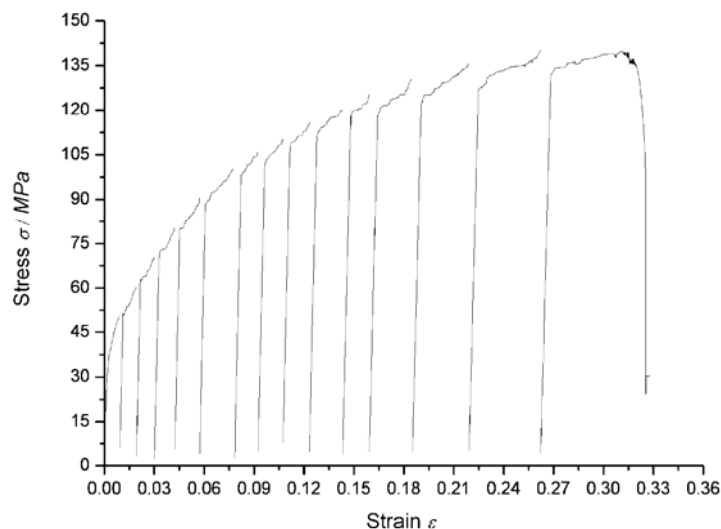
Figure 1. Stress-strain curves in loading-unloading conditions.

3. Results and discussions

3.1. Damage constitutive model

The continuum damage mechanics is adopted to predict fracture in structures. According to Kasyanov [7], who first introduced the damage variable D defined in Eq. (1) to characterize the deterioration of the mechanical properties due to material damage.

$$D = \frac{A_D}{A} \tag{1}$$

Where A and A_D are the cross-sectional area of the loaded region and the reduced area due to microdefects, respectively. In Eq. (1), D can be also represented by the elastic modulus using Lemaitre's principle [11],

$$D = 1 - \frac{E_D}{E} \tag{2}$$

Where E and E_D are the elastic modulus of virgin material and damaged material, respectively. Thus, E_D decreases as the degree of damage in the material increases.

The material fractures when the damage increases to a certain degree, and the value of damage variable D is

$$D_0 \le D \le D_C < 1 \tag{3}$$

Where D_0 and D_C are the value of initial damage and critical damage, respectively.

Fig.2 shows the variation of the elastic modulus and damage with the plastic strain. It can be found that the elastic modulus decreased and the damage increased with the deformation. The fitting lines show good linearity and the correlation factors R are both more than 0.99. The relation between damage variable and plastic strain can be expressed as,

$$D = -0.011 + 0.745\varepsilon_{\mathrm{p}} \tag{4}$$

Damage occurs in the material when the plastic strain accumulates to a certain extent, and the plastic strain in the occurrence of damage is the threshold strain value for damage, ε_D, which can be identified as 0.015 by Eq.(4). Fracture occurs in the material when the damage accumulates to a certain extent, and the critical damage value D_C is calculated as 0.184 combined with the results of Fig.2. Correspondingly, the critical plastic strain ε_C is 0.262.
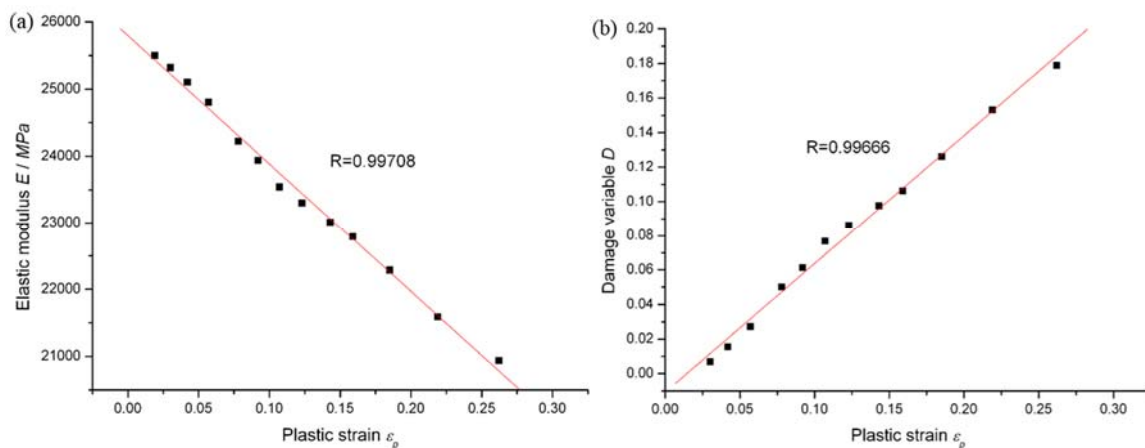
Figure 2. Relation between (a) elastic modulus, (b) damage and plastic strain.

The traditional design of forming process is $\sigma_s \le \sigma \le \sigma_b$ or $\varepsilon_s \le \varepsilon \le \varepsilon_b$. It is illustrated that the material will not fracture when the working stress or strain is lower than fracture strength σ_b or fracture strain ε_b after yield based on the traditional strength theory. However, the traditional viewpoint cannot satisfactorily explain some unexpected accidents, and many cold-working structures fracture even the stress is lower than fracture strength. According to the results of this study, the materials will fracture when the stress is lower than fracture strength for the damage increasing. So the values of D_C and ε_C calculated above can be used to characterize the damage degree and the limit of safe service in the cold-working structures.

3.2. Toughness indicator and energy analysis
Double atoms model is a theoretical model to investigate the structural design of high polymer materials at the molecular level of materials [12]. Orowan has proposed that the fracture strength of ductile material obeys a sine relationship of double atoms model [13]. In this paper, the stress-strain cure is regarded as an equivalent sine relation according to the principle of double atoms model.

Assumed that

$$y = A \sin \frac{\pi x}{2a} \tag{5}$$

An equivalent slope at the elastic-plastic transition point in sine curve is defined as $\tilde{E}$ which is calculated as following equation

$$\tilde{E} = \frac{\pi m (\sigma_b - 0.363 \sigma_s)}{2(\varepsilon_b - \varepsilon_0)} \tag{6}$$

where, $\tilde{E}$ is the tangent modulus, m is the coefficient, σ_s is the subsequent yield strength, σ_b is the fracture strength, ε_0 is the initial yield strain and ε_b is the fracture stain. The tangent modulus $\tilde{E}$ is proposed to represent the toughness performance after plastic deformation.

The toughness indicator is used to indicate the material toughness and the toughness directly affect the mechanical properties of material. Toughness indicator ϕ is formulated as

$$\phi = \left(\frac{\sigma_b - 0.363 \sigma_0}{\varepsilon_b} \right) \left(\frac{\varepsilon_b - \varepsilon_0}{\sigma_b - 0.363 \sigma_s} \right) \tag{7}$$

Where, σ_0 is the initial yield strength.

Two new surfaces will form due to damage nucleation, growth and coalescence according to CDM [14]. The total surface energy is contain two parts, $e = e_s + e_p$, where, e_s is the surface energy and e_p is the plastic deformation energy. Gilman [15] established the relationship between e_p and e_s as

$$e_p = 9 e_s \ln \frac{G}{\pi \sigma_s} \approx 9 e_s \ln \frac{\sigma_b}{\sigma_s} \tag{8}$$

Where, *G* is the shear modulus.
The plastic deformation energy indicator χ is calculated as

$$\chi = \frac{e_p}{e_s} \approx 9 \ln \frac{\sigma_b}{\sigma_s} \tag{9}$$

According to the repeated loading-unloading experimental values of AA5052, the relation between subsequent yield strength and initial plastic strain is established, as shown in Fig.3 (a). Obviously, the work-hardening occurs and the subsequent yield strength increases as exponential form. According to the loading-unloading data of strain hardening plastic material, the relation between subsequent yield strength and initial plastic strain can be assumed as

$$\sigma_s = f(\varepsilon_0) = \sigma_0 + K\varepsilon_0^{\ n} \tag{10}$$

Where K is a strength coefficient and n is the strain hardening exponent. The fitting relation is

$$\sigma_s = f(\varepsilon_0) = 39.255 + 198.72\varepsilon_0^{\ 0.439} \tag{11}$$

And the correlation factor of this fitting line R is more than 0.99.

The yield strength after a certain degree of deformation can be obtained according to Eq. (11). It is an important reference for the analysis of toughness performance, surface energy and plastic deformation energy in deformation zone and the expanding model after the crack initiation.
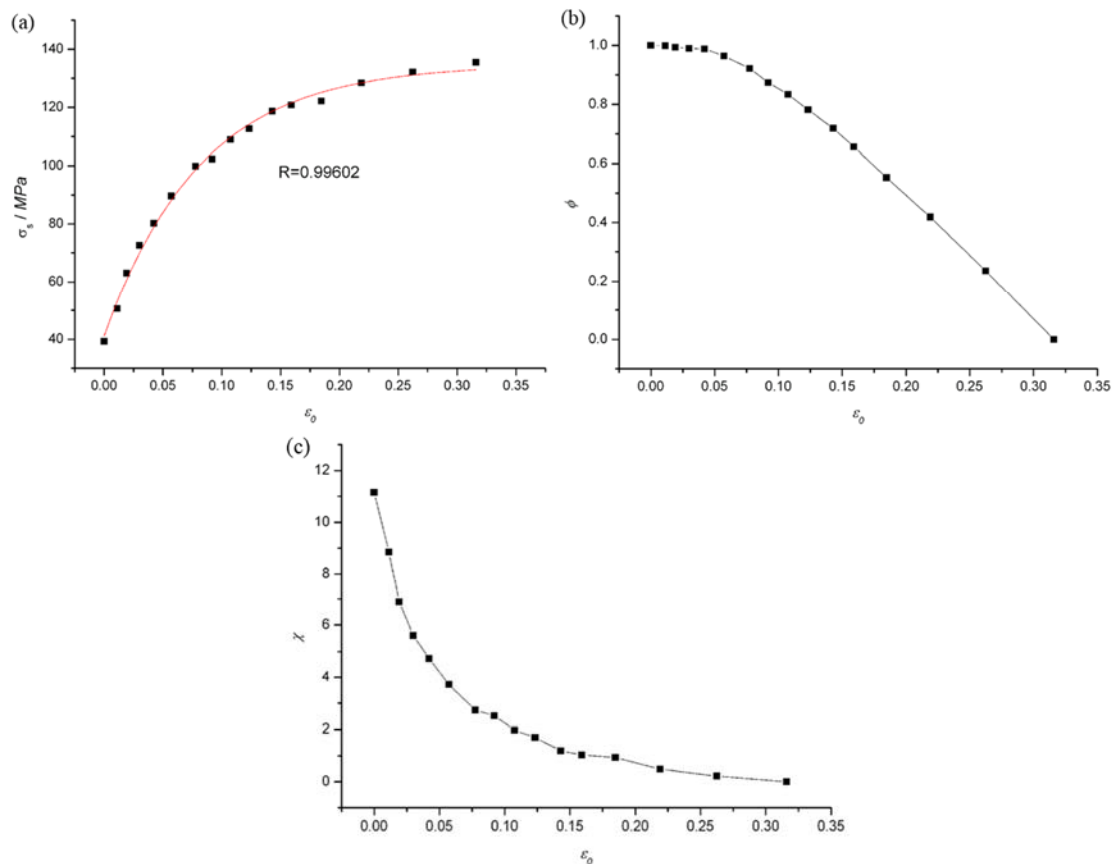
Figure 3. Relation between (a) subsequent yield stress, (b) equivalent toughness indicator, (c) equivalent toughness indicator and plastic strain.

The toughness indicator ϕ and plastic deformation energy indicator χ are calculated according to Eqs. (7) and (9). The variation of toughness indicator and plastic deformation energy indicator with the initial plastic strain are shown in Fig.3 (b) and Fig.3 (c). It can be seen the toughness indicator decreases slowly at first and then rapidly with the increase of the initial plastic strain, and the plastic deformation energy indicator decreases quickly at first and then slowly. At the onset of plastic deformation, the material is undamaged or less damaged and the material absorbs more plastic deformation energy and performs good ductile property. With development of plastic strain, damage accelerated and the absorbed energy is mainly dissipated to form new void surface and mechanical properties of materials are degraded.

4. Conclusion

Repeated loading-unloading test were conducted on 5052 aluminum alloy. It was found that the subsequent yield strength increased after the yield until fracture. It illustrated that the plastic deformation of material was accompanied by yield hardening, and then the yield hardening model was established. The toughness indicator and plastic deformation energy indicator were applied to characterize the plastic performance after yield. It was shown that both indicators decreased with the increase of load. The toughness indicator decreased slowly at first and then rapidly with the increase of the initial plastic strain and the plastic deformation energy indicator decreased quickly at first and then slowly, which can well characterize the material toughness in the deformation process.

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