

## Effects of temperature and strain rate on critical damage value of AZ80 magnesium alloy

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Received 23 September 2009; accepted 30 January 2010

**Abstract:** A series of AZ80 billets were compressed with 60% height reduction on hot process simulator at 250, 300, 350, 400 under strain rates of 0.01, 0.1, 1 and  $10\text{ s}^{-1}$ . In order to predict the occurrence of surface fracture, the values of the Cockcroft-Latham equation were calculated by the corresponding finite element numerical algorithm developed. A concept about damage incremental ratio in plastic deformation was defined as the ratio of damage increment at one step to the accumulated value. A method of finding the intersection of incremental ratio varying curve and simulation step axis was brought forward to make the fracture step certain. Then, the effects of temperature and strain rate on critical damage value were achieved. The results show that the critical damage value is not a constant but changes in a range of 0.0218–0.3780. It decreases significantly with the increase of strain rate at a certain temperature. While under a certain strain rate, the critical damage value has little change with the increase of temperature.

**Key words:** AZ80 magnesium alloy; critical damage value; compaction; finite element analysis

### 1 Introduction

An important concern in metal-forming processes is whether the desired deformation can be accomplished without fracture of the workpiece. In industrial practice, however, the empirical know-how of the designer is decisive for the fracture-free quality of the products, but often requires very costly trial-and-error[1–2]. Thus, there is a critical need for predicting and preventing fracture, which is a major feature of the forming processes and the quality of the products.

Most bulk metal-forming processes may be limited by ductile fracture e.g. the occurrence of internal or surface fracture in the workpiece. If it was possible to predict the conditions of the deforming workpiece which lead to fracture, it may be feasible to choose appropriate process conditions and to modify the forming processes in order to produce sound products[3–4].

Historically, ductile-fracture criteria are based on experimental work that utilizes a deformation process related to actual industrial applications. So far, the fracture criterion such as Cockcroft-Latham is suited for tenacity fracture in bulk metal-forming simulation. Usually, the critical damage value is considered as an

constant of material like yield stress or stress limit. Cockcroft and Latham hasn't expounded whether the critical damage value depends on the temperature and strain rate[5–9]. In this study, for AZ80 magnesium alloy, the relations between critical damage value and temperature and strain rate were analyzed based on a series of compressing tests data and damage data by numerical computation.

### 2 Experimental

The chemical compositions of AZ80 magnesium alloy were 8.90% Al, 0.53% Zn, 0.2% Mn, 0.008% Si, 0.004% Fe, 0.008% Cu, 0.008% Ni (mass fraction).

A computer-controlled, servo-hydraulic Gleeble 1500 machine was used for compression testing. It can be programmed to simulate both thermal and mechanical industrial processing variables in a wide range of hot-deformation conditions[10]. The specimens were resistance heated to the deformation temperature at a heating rate of  $1\text{ }^{\circ}\text{C/s}$  and held at that temperature for 180 s. The homogenized ingot was scalped to diameter of 10 mm and height of 12 mm with grooves on both sides filled with machine oil mingled using graphite powder as lubrication during isothermal hot compression tests at

250, 300, 350, 400 °C and strain rates of 0.01, 0.1, 1 and 10 s<sup>-1</sup>.

### 3 Analysis of damage in deformation

#### 3.1 Stress—strain behavior

The true compressive stress—strain curves of AZ80 magnesium alloy are shown in Fig.1. The flow stress as well as the shape of the flow curves is sensitively dependent on temperature and strain rate[11]. For all of specimens, after initial yielding, the flow stress decreases monotonically with different softening rates. For a specific strain rate, the flow stress decreases markedly with the increase of temperature, while for a specific temperature, the flow stress increases markedly with the increase of strain rate. Only for strain rate of 10 s<sup>-1</sup>, fracture is seen to occur after a dynamic softening.

For the simulation of plastic deformation process, the material model for billet can be defined by inputting the true stress—strain curve data (as Fig.1). The yield stress of AZ80 magnesium alloy under uniaxial conditions as a function of strain ( $\bar{\epsilon}$ ), strain rate ( $\dot{\bar{\epsilon}}$ ), and temperature ( $T$ ) can also be considered as flow stress. The metal starts flowing or deforming plastically when the applied stress reaches the value of yield stress.

#### 3.2 Cockcroft and Latham damage

Cockcroft and Latham, based on cumulative

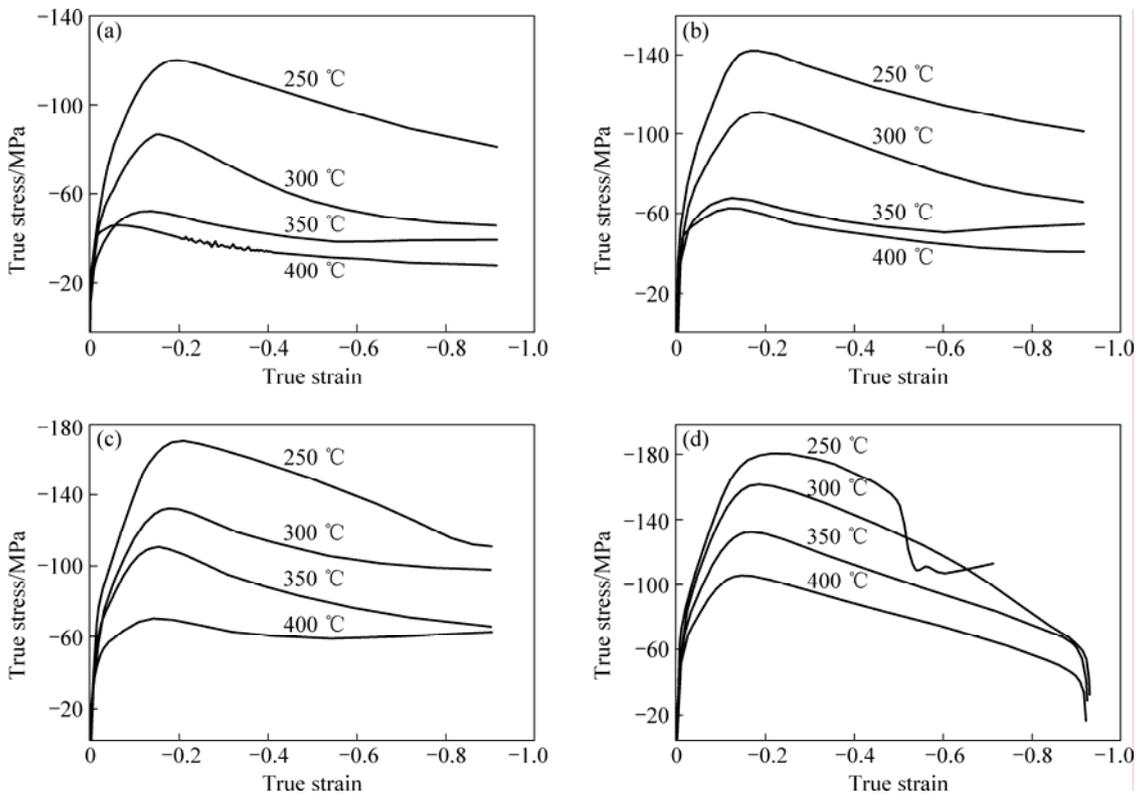
damage theory, developed a damage computation module which has been applied successfully to a variety of loading situations[12–14]. It has been used to assess the degree of working imposed on magnesium alloy in such processes as extrusion, rolling and upsetting by tools. The damage in plastic deformation is defined by Cockcroft and Latham as an amount of work that the ratio of maximum tensile stress  $\sigma_T$  to effective stress  $\bar{\sigma}$  carries out through the applied equivalent strain  $\bar{\epsilon}$  in a metal-working process, i.e.

$$C = \int_0^{\bar{\epsilon}_f} \frac{\sigma_T}{\bar{\sigma}} d\bar{\epsilon} \tag{1}$$

where  $\bar{\epsilon}_f$  is the total equivalent strain at the end of forming process. The magnitude of  $C$  cannot exceed a maximum value  $C_{max}$  (critical damage value) to failure. By comparing  $C$  with  $C_{max}$ , the risk of material failure during processing is assessed. In order to calculate  $C$  by FE simulation, Eq.(1) has to be converted to an appropriate discrete expression convenient for FE code:

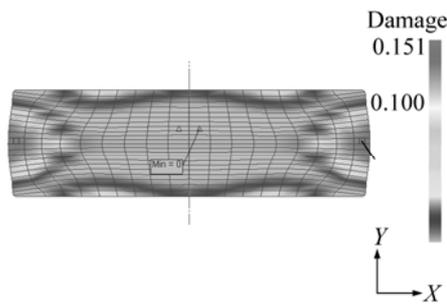
$$C = \int_0^{\bar{\epsilon}_f} \frac{\sigma_T}{\bar{\sigma}} \frac{d\bar{\epsilon}}{dt} dt = \int_0^{t_f} \frac{\sigma_T}{\bar{\sigma}} \dot{\bar{\epsilon}} dt \cong \sum_0^{t_f} \frac{\sigma_T \dot{\bar{\epsilon}} \Delta t}{\bar{\sigma}} \tag{2}$$

where  $\dot{\bar{\epsilon}}$  is the equivalent strain rate as Eq.(1) calculated from the individual principal strain-rate components, and  $\Delta t$  is the variable time increment used in the FE analysis.



**Fig.1** True stress—strain curves of AZ81 Mg alloy at different strain rates and temperatures: (a)  $\dot{\epsilon}=0.01 \text{ s}^{-1}$ ; (b)  $\dot{\epsilon}=0.1 \text{ s}^{-1}$ ; (c)  $\dot{\epsilon}=1 \text{ s}^{-1}$ ; (d)  $\dot{\epsilon}=10 \text{ s}^{-1}$

According to cumulative damage theory, the damage value a moment ago is less than that a moment later during a compressing process. Therefore, the maximum value will appear at the last simulation step, but it does not mean fracture step. Fig.2 shows the damage distribution at the last step (height reduction of 60%) at 300 °C and strain rate of 0.01 s<sup>-1</sup>. From the simulation results, it can be seen that the maximum damage value appears in the region of upsetting drum, while the minimal value appears in the middle region.



**Fig.2** Damage distribution at last step (height reduction of 60%) at 300 °C and strain rates of 0.01 s<sup>-1</sup>

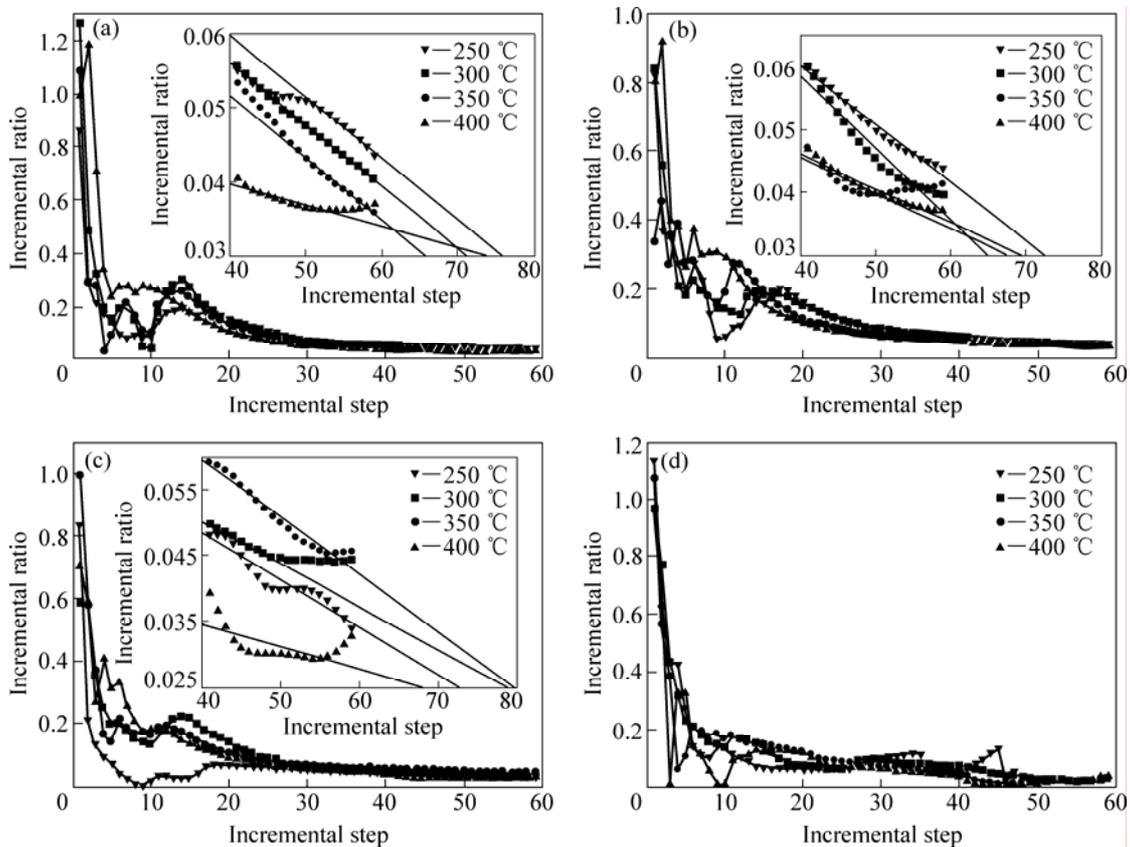
### 3.3 Determination of critical damage value of AZ80

The Cockcroft-Latham constant,  $C_{max}$  (critical

damage value), is dependent on the same material parameters that forming limits are dependent on. Metallurgical properties such as the microstructure, alloy constants, grain size and grain form, and non-metallic inclusion content, whilst having a small effect on the strength and the hardness, have a significant effect on the critical damage value[15]. In order to predict the occurrence of surface fracture, the value of the Cockcroft-Latham equation expressed by means of Eq.(1) is calculated at the integration point inside the elements. Furthermore, a concept about incremental ratio of Cockcroft-Latham damage in plastic deformation ( $R_{step}$ ) is brought out and defined as the ratio of the damage increment at one step ( $\Delta D$ ) to the accumulated value ( $D_{acc}$ ):

$$R_{step} = \Delta D / D_{acc} \tag{3}$$

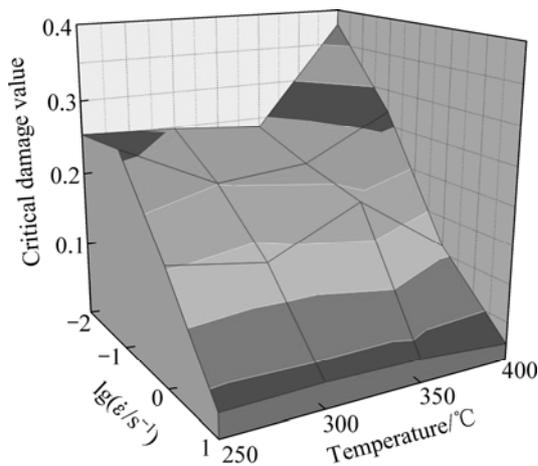
Fig.3 shows this incremental ratio varying during the upsetting processes at different temperatures and different strain rates. It can be seen that  $R_{step}$  decreases to the trough point rapidly, then it has a slight increase, soon after which it decreases to zero gradually. The zero point has a tolerances of 0–0.03. In this study, the zero point is assumed as the fracture time, and the other horizontal curve segment is considered as the dynamic



**Fig.3** Incremental ratio varying of Cockcroft-Latham damage during compressing process at different temperatures and different strain rates: (a)  $\dot{\epsilon} = 0.001 \text{ s}^{-1}$ ; (d)  $\dot{\epsilon} = 0.1 \text{ s}^{-1}$ ; (c)  $\dot{\epsilon} = 1 \text{ s}^{-1}$ ; (d)  $\dot{\epsilon} = 10 \text{ s}^{-1}$

softening due to an increase of dislocation density and the dislocation multiplication rate.

To find the fracture time (step), the point arrays after step 40 are picked out from each incremental ratio varying curve and fitted linearly (as shown in Fig.3). The intersection of line fitted and horizontal axis is obtained, and it is made certain as the fracture step. Then, the simulation with only 60 steps is continued to run until the fracture. The maximum cumulative damage value at last step or the critical damage value is computed. By this way, the critical damage value of AZ80 magnesium alloy can be achieved. Fig.4 shows the effects of temperature and strain rate on critical damage value of AZ80 magnesium alloy. It can be seen that the critical damage value is not a constant but changes in a range of 0.021 8–0.378 0. Further, the critical damage value decreases significantly with strain rate increasing at a certain temperature. While under a certain strain rate, the critical damage value has little change with the increase of temperature. It can be seen that the critical damage value depends on the temperature and strain rate, and it is more sensitive to strain rate.



**Fig.4** Effects of temperature and strain rate on critical damage value of AZ80 magnesium alloy

## 4 Conclusions

1) The true compressive stress—strain curves of AZ80 magnesium alloy deformed at four temperatures under four strain rates are obtained. The flow stress as well as the shape of the flow curves is sensitively dependent on temperature and strain rate.

2) According to cumulative damage theory, the maximum value appears at the last simulation step, but it does not mean fracture step. Thus, a method of finding the intersection of incremental ratio varying curve and simulation step axis is brought forward to make the fracture step certain.

3) The critical damage value is not a constant but

changes in a range of 0.0218–0.378. It decreases significantly with strain rate increasing at a certain temperature. While under a certain strain rate, the critical damage value has little change with temperature increasing. In a word, it is more sensitive to strain rate.

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(Edited by ZHAO Jun)