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Damage evolution of metallic materials during high temperature plastic deformation①

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[Abstract] The damage evolution of high temperature plastic deformation of metallic materials was studied by use of continuum damage mechanics (CDM) theory. Based on thermodynamics, on a damage variable D and Zener-Hollomon parameter Z, and on the effective stress concept, a damage evolution model of high temperature plastic deformation was derived and was used to analyze the damage evolution of 1420 Al-Li alloy during high temperature plastic deformation. The model that is verified by tests can also be applied to the materials that are loaded prorata or out of proportion during high temperature plastic deformation. It extends the applied scope of damage mechanics.

[Key words] damage mechanics; Zener-Hollomon parameter; damage variable
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1 INTRODUCTION

A damage evolution model of high temperature plastic deformation is derived in this paper by using some basic concepts, principles and methods of damage mechanics. The model is testified by being used to analyze the damage evolution of the cast 1420 Al-Li alloy. So as to establish the damage evolution model of Al-Li alloy during high temperature plastic deformation. The damage mechanics is applied to the process of materials. It also can be concluded into theory of the establishment of materials processing techniques. The method used in this paper is also suitable for the other metallic materials. It extends the applied scope of damage mechanics.

2 ESTABLISHMENT OF DAMAGE EVOLUTION MODEL OF HIGH TEMPERATURE PLASTIC DEFORMATION

Assuming the damage is isotropic. According to Ref.[1] the common form of the model of damage evolution is

$$\dot{D} = -\frac{\partial \Psi}{\partial Y} \qquad (1)$$

where Ψ is the residual dissipation potential, Y is the damage strain-energy release rate.

And Ψ can be written into the form of the couple of the plastic cumulated strain rate $\dot{p}$ and micro-plastic strain rate $\dot{\pi}$ between plastic and damage[2], then we can get:

$$\Psi = \Psi_p + \Psi_D(Y, \dot{p}, \dot{\pi}, \varepsilon^e, D) + \Psi_\pi$$

There are so few data concerning the micro-plastic dissipation potential Ψ_π so that it's usually ignored.

According to the principle of strain equivalence, the model of coupled damage's isotropy work hardening can adopt Gorche and Doege's model[3]. They deduced the yield condition model considering the cavity's interaction, based on the Gurson[4] model considering the cavity's grow-up. Then

$$f = \frac{3}{2}\frac{\bar{\sigma}^2}{2\sigma_s^2(1-D)^2} - 1 = 0 \qquad (2)$$

where $\bar{\sigma}$ is the basic material's effective stress, σ_s is the yield stress. Namely Ψ_p can be taken as the yield function $f = 0$.

In reference to many damage models proposed, Ψ_D can be written as

$$\Psi_D(Y, \dot{p}, \dot{\pi}, \varepsilon^e, D) = \frac{1}{2}\cdot\frac{Y^2}{S}\left[\frac{\dot{p}+\dot{\pi}}{1-D}\right]$$

where S is the material constant parameter depending on temperature.

So

$$\dot{D} = -\frac{\partial \Psi}{\partial Y} = -\frac{\partial \Psi_D}{\partial Y} = -\frac{Y}{S}\left[\frac{\dot{p}+\dot{\pi}}{1-D}\right]$$

In his study, Lemaitre[5] pointed out that $\dot{\pi} \doteq 0$ in the scale of plasticity. Then

$$\dot{D} = -\frac{Y}{S}\left[\frac{\dot{p}}{1-D}\right] \qquad (3)$$

Since the larger the damage variable D, the larger the absolute value of the damage strain energy release rate Y. Then, the relationship between the damage strain energy release rate Y and the damage variable D can be expressed as[6]:

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$$Y = A\exp\left[B\frac{\sigma_m}{\sigma_{eq}}\right]D^r\bar{\sigma}$$

where σ_m is the mean stress, σ_{eq} is the equivalent stress, σ_m/σ_{eq} is the triaxiality stress ratio, A, B and r are constants related to the materials and the deformation conditions.

It can be deduced from Eqn. (2) that:

$$\bar{\sigma} = \sqrt{\frac{2}{3}}\sigma_s(1 - D)$$

then

$$Y = A\exp\left[B\frac{\sigma_m}{\sigma_{eq}}\right]D^r\sqrt{\frac{2}{3}}\sigma_s(1-D) = \sqrt{\frac{2}{3}}A\exp\left[B\frac{\sigma_m}{\sigma_{eq}}\right](1-D)D^r\sigma_s$$

Eqn. (3) can be written as

$$\dot{D} = -\frac{Y}{S}\frac{\dot{p}}{(1-D)} = -\frac{1}{S}\sqrt{\frac{2}{3}}A\exp\left[B\frac{\sigma_m}{\sigma_{eq}}\right](1-D)\cdot D^r\sigma_s\frac{\dot{p}}{(1-D)} = -\sqrt{\frac{2}{3}}\frac{1}{S}A\exp\left[B\frac{\sigma_m}{\sigma_{eq}}\right]D^r\sigma_s\dot{p} \quad (4)$$

Since the damage is linear with the plastic strain rate, according to Ref. [5], r is taken as naught. Supposing p_D be the accumulated plastic strain critical value, when $p \leqslant p_D$, $D = 0$. Integrating Eqn. (4), then

$$D = -\sqrt{\frac{2}{3}}\frac{A}{S}\exp\left[B\frac{\sigma_m}{\sigma_{eq}}\right]\sigma_s(p - p_D) \quad (5)$$

Assuming p_R is the accumulated plastic strain when material is broken. Then the correspondent critical value of damage variable D_C is

$$D_C = -\sqrt{\frac{2}{3}}\frac{A}{S}\exp\left[B\frac{\sigma_m}{\sigma_{eq}}\right]\sigma_s(p_R - p_D) \quad (6)$$

Eqn. (5) divided by Eqn. (6) is

$$D = D_C\frac{p - p_D}{p_R - p_D} \quad (7)$$

Under the one-dimensional case[7, 8]

$$\frac{p_D}{p_R} = \frac{\varepsilon_D}{\varepsilon_R} \quad (8)$$

where ε_D, ε_R are the damage equivalent strain threshold and the rupture equivalent strain.

Substituting Eqn. (8) into Eqn. (7),

$$D = D_C\left[\frac{p(\varepsilon_R/p_R) - \varepsilon_D}{\varepsilon_R - \varepsilon_D}\right] \quad (9)$$

In one-dimensional case, $\sigma_m/\sigma_{eq} = 1/3$, $p_D = 0$, $p_R = \varepsilon_R$ (the elastic deformation is ignored), from Eqn. (5), we have

$$p_R = \varepsilon_R = -\sqrt{\frac{3}{2}}\frac{S}{A}\frac{D_C}{\exp\left[\frac{1}{3}B\right]\sigma_s} \quad (10)$$

And substituting Eqn. (10) into Eqn. (6), then

$$-\sqrt{\frac{3}{2}}\frac{A}{S}\exp\left[\frac{1}{3}B\right]\sigma_s\varepsilon_R = -\sqrt{\frac{3}{2}}\frac{A}{S}\exp\left[B\frac{\sigma_m}{\sigma_{eq}}\right]\sigma_s p_R$$

Thus p_R under triaxiality stress case can be written as

$$p_R = \varepsilon_R/\exp\left[B\left[\frac{\sigma_m}{\sigma_{eq}} - \frac{1}{3}\right]\right] \quad (11)$$

Substituting Eqn. (11) into Eqn. (9), then

$$D = D_C\left[\frac{p\exp\left[B\left[\frac{\sigma_m}{\sigma_{eq}} - \frac{1}{3}\right]\right] - \varepsilon_D}{\varepsilon_R - \varepsilon_D}\right] = \frac{D_C}{\varepsilon_R - \varepsilon_D}\left\{\exp\left[B\left[\frac{\sigma_m}{\sigma_{eq}} - \frac{1}{3}\right]\right]p - \varepsilon_D\right\} \quad (12)$$

The materials parameters D_C, ε_R and ε_D are related to the deformation temperature T and strain rate $\dot{\varepsilon}$.

It has been pointed out[9～12], for metal and alloy deformation, the general influence caused by deformation temperature T and strain rate $\dot{\varepsilon}$ can be expressed by introducing temperature-compensated strain rate parameter, i. e. Zener-Hollomon parameter:

$$Z = \dot{\varepsilon}\exp(Q/RT) = A[\sinh(\alpha\sigma)]^n$$

where A, n, α and Q are material constants, R is gas constant. It means that the materials parameters D_C, ε_R, ε_D are the functions of Zener-Hollomon parameter.

For high temperature plastic deformation, Eqn. (12) becomes

$$D = \frac{D_{C(Z)}}{\varepsilon_{R(Z)} - \varepsilon_{D(Z)}}\cdot\left\{\exp\left[B\left[\frac{\sigma_m}{\sigma_{eq}} - \frac{1}{3}\right]\right]p - \varepsilon_{D(Z)}\right\} \quad (13)$$

where $D_{C(Z)}$ is the critical value of damage variable in one-dimensional tensile test while $\varepsilon_{R(Z)}$, $\varepsilon_{D(Z)}$ are related to the rupture equivalent strain and the damage equivalent strain threshold respectively. They can be measured by the one direction tensile test under different deformation conditions. According to Ref. [7], parameter B can be taken as 1.0.

Then Eqn. (13) is the damage evolution model of high temperature plastic deformation of materials.

Under one-dimension stress, for $\sigma_m/\sigma_{eq} = 1/3$, thus from Eqn. (13), we get

$$D = \frac{D_{C(Z)}}{\varepsilon_{R(Z)} - \varepsilon_{D(Z)}}[p - \varepsilon_{D(Z)}] \quad (14)$$

If the value of $\varepsilon_{R(Z)}$, $\varepsilon_{D(Z)}$ and $D_{C(Z)}$ can be determined by the tensile test in different deformation conditions, after the plastic deformation with random loading methods the value of damage variable D of materials will be confirmed.

3 EXPERIMENTAL

This experimental material was 1420 Al-Li alloy whose chemical compositions are listed in Table 1.

This alloy was smelted and cast by IM. It was

Table 1 Chemical compositions of 1420 Al-Li alloy (mass fraction, %)

Cu	Mg	Si	Li	Fe
0.05	5.44	0.013	2.15	0.02
Zr	Na	Ti	H	
0.12	0.0004	0.05	0.6	

melted and fined under the protection of flux, and being cast to circle ingots with diameter of 405 mm and length of 1200 mm, and with water-cooling moulds under argon atmosphere. After the ingots being homogenized at 455 ℃ for 12 h, from them small columnar samples with diameter of 10 mm and length of 125 mm were machined whose ends were machined to thread M10 × 1.5. The tensile tests of equivalent temperatures and constant strain rates were performed on Gleeble-1500 Thermal Simulator and the samples were loaded-unloaded repeatedly (where the strain step is 0.05 s^{-1}) till rupture. Computer fully controlled the deformation process and automatically gathered the true stress-strain curves of the experimental materials. The deformation temperatures used for 1420 Al-Li alloy were 300, 350 and 400 ℃ and the strain rates used were 0.001, 0.01, 0.1 and 1.0 s^{-1} for each temperature.

4 ESTABLISHMENT OF MATERIAL PARE- METERS AND MODEL VERIFICATION

4.1 Establishment of material parameters

According to Kachanov and Lemaitre[2]:

$$D = 1 - \tilde{E}/E \tag{15}$$

Where E is the elastic mould of the material without damage. $\tilde{E}$ is that of the damaged. The actual values of high temperature plastic deformation damage variables of 1420 Al-Li alloy can be computed by this equation. It's shown in Fig. 1 as the black dot while Fig. 1 only shows part of the experiment results.

Table 2 shows the damage variables' critical values and the destructive strain values of 1420 Al-Li alloy plastic deformation experiments under different deformation conditions.

4.2 Model verification

Substituting the associated materials parameters into Eqn. (14), the damage evolution prediction values of high temperature 1420 Al-Li alloy of plastic deformation are computed and compared with the actual values. The errors are within 6%. So the damage evolution model of high temperature plastic deformation of materials is verified. And it's effective and feasible for the studied material.

Fig. 1 shows that the damage emerges while 1420 Al-Li alloy begins plastic deformation under each test. With development of deformation, material

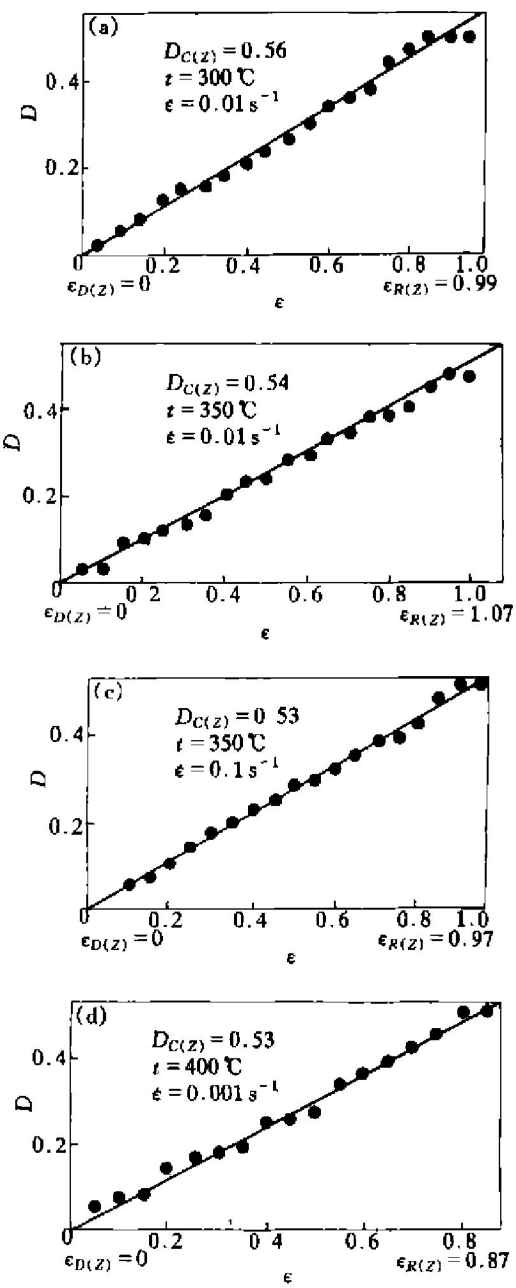

Fig. 1 Comparison between model predictions damage evolution curves and experimental results

Table 2 Results of high temperature damage experiment

Deformation condition	$D_{C(z)}$	$\varepsilon_{R(z)}$
300 ℃, 0.001 s^{-1}	0.60	0.41
350 ℃, 0.001 s^{-1}	0.58	0.58
350 ℃, 0.1 s^{-1}	0.53	0.97
400 ℃, 0.001 s^{-1}	0.53	0.87
400 ℃, 0.1 s^{-1}	0.47	0.41
Deformation condition	$D_{C(z)}$	$\varepsilon_{R(z)}$
300 ℃, 0.01 s^{-1}	0.56	0.99
350 ℃, 0.01 s^{-1}	0.54	1.07
350 ℃, 1.0 s^{-1}	0.59	0.42
400 ℃, 0.01 s^{-1}	0.58	0.57

emerges positive damage evolution and the value of the damage rise linearly, which is in accordance to the rule of Eqn. (14).

5 CONCLUSIONS

1) The Zener-Hollomon parameters, which considers the comprehensive effects of deformation temperature and strain rate, are introduced into damage mechanics. On the base of it, the high temperature plastic deformation damage evolution model is deduced according to the continuous medium damage mechanics.

2) It's analyzed and verified by experiments that the damage variable is linear with the associated strain while the three axes angles have a most conspicuous effect on it.

3) The model proposed can be used to describe the high temperature plastic deformation process of 1420 Al-Li alloy, and the prediction value by the model inosculates the experimental value perfectly, while the errors are within ±6%.

4) The optimum processing techniques is that strain rate is less than 1.0 s^{-1} and deformation temperature is from 350 ℃ to 400 ℃ during high temperature plastic deformation of 1420 Al-Li alloy.

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